

This is a repository copy of *Distinctive phytohormonal and metabolic profiles of Arabidopsis thaliana and Eutrema salsugineum under similar soil drying*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/141366/>

Version: Accepted Version

---

**Article:**

Pinheiro, Carla, Dickinson, Elizabeth [orcid.org/0000-0001-8961-3230](https://orcid.org/0000-0001-8961-3230), Marriott, Andrew et al. (9 more authors) (2019) Distinctive phytohormonal and metabolic profiles of *Arabidopsis thaliana* and *Eutrema salsugineum* under similar soil drying. *Planta*. pp. 1417-1433. ISSN 0032-0935

<https://doi.org/10.1007/s00425-019-03095-5>

---

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

# Planta

## Distinctive phytohormonal and metabolic profiles of Arabidopsis thaliana and Eutrema salsugineum under similar soil drying

--Manuscript Draft--

<b>Manuscript Number:</b>														
<b>Full Title:</b>	Distinctive phytohormonal and metabolic profiles of Arabidopsis thaliana and Eutrema salsugineum under similar soil drying													
<b>Article Type:</b>	Original Article													
<b>Corresponding Author:</b>	Carla Pinheiro Universidade Nova de Lisboa Instituto de Tecnologia Quimica e Biologica PORTUGAL													
<b>Corresponding Author Secondary Information:</b>														
<b>Corresponding Author's Institution:</b>	Universidade Nova de Lisboa Instituto de Tecnologia Quimica e Biologica													
<b>Corresponding Author's Secondary Institution:</b>														
<b>First Author:</b>	Carla Pinheiro													
<b>First Author Secondary Information:</b>														
<b>Order of Authors:</b>	Carla Pinheiro Elizabeth Dickinson Andrew Marriott Isa Catarina Ribeiro Marta Pintó-Marijuan Carla António Olfa Zarrouk Maria Manuela Chaves Ian Catarina Dodd Sergi Munné-Bosch Jane Thomas-Oates Julie Wilson													
<b>Order of Authors Secondary Information:</b>														
<b>Funding Information:</b>	<table> <tr> <td>Fundação para a Ciência e a Tecnologia</td> <td>PhD Carla António PhD Olfa Zarrouk</td> </tr> <tr> <td>Daphne Jackson Trust</td> <td>PhD Elizabeth Dickinson</td> </tr> <tr> <td>Biotechnology and Biological Sciences Research Council</td> <td>PhD Andrew Marriott</td> </tr> <tr> <td>ITQB NOVA R&amp;D GREEN-it (UID/Multi/04551/2013)</td> <td>Not applicable</td> </tr> <tr> <td>Northern Way Initiative</td> <td>Not applicable</td> </tr> <tr> <td>Engineering and Physical Sciences Research Council (EP/K039660/1; EP/M028127/1)</td> <td>Not applicable</td> </tr> </table>		Fundação para a Ciência e a Tecnologia	PhD Carla António PhD Olfa Zarrouk	Daphne Jackson Trust	PhD Elizabeth Dickinson	Biotechnology and Biological Sciences Research Council	PhD Andrew Marriott	ITQB NOVA R&D GREEN-it (UID/Multi/04551/2013)	Not applicable	Northern Way Initiative	Not applicable	Engineering and Physical Sciences Research Council (EP/K039660/1; EP/M028127/1)	Not applicable
Fundação para a Ciência e a Tecnologia	PhD Carla António PhD Olfa Zarrouk													
Daphne Jackson Trust	PhD Elizabeth Dickinson													
Biotechnology and Biological Sciences Research Council	PhD Andrew Marriott													
ITQB NOVA R&D GREEN-it (UID/Multi/04551/2013)	Not applicable													
Northern Way Initiative	Not applicable													
Engineering and Physical Sciences Research Council (EP/K039660/1; EP/M028127/1)	Not applicable													
<b>Abstract:</b>	Although plants perceive and respond to soil drying via a series of concurrent physiological and molecular events, drought tolerance differs greatly within the plant kingdom. While Eutrema salsugineum (formerly Thellungiella salsuginea) is regarded													

	<p>as more stress tolerant than its close relative <i>Arabidopsis thaliana</i>, their responses to soil water deficit have not been compared. To ensure a similar rate of soil drying for the two species, daily soil water depletion was controlled to 5-10 % of the soil water content. While partial stomatal closure occurred earlier in <i>Arabidopsis</i> (Day 4) than <i>Eutrema</i> (from Day 6 onwards), thereafter both species showed similar stomatal sensitivity to drying soil. Nonetheless, both targeted and untargeted metabolite analysis showed larger responses in <i>Arabidopsis</i> in both early/mild drought (Days 1, 3, 5 – no significant change in leaf relative water content, RWC) and late/severe drought (Day 12 – circa 80 % decrease in leaf RWC). <i>Arabidopsis</i> (but not <i>Eutrema</i>) showed early peaks in foliar abscisic acid (ABA), jasmonic acid (JA) and salicylic acid (SA) contents. <i>Arabidopsis</i> showed greater metabolic adjustment than <i>Eutrema</i> during both early drought stress (428 versus 35 variables significantly changing) and severe drought (607 versus 171 variables significantly changing). Different sugar profiles between species were accompanied by opposing patterns in the bioactive cytokinin profile responses. The distinctive metabolic responses of each species during early drought, which occurred prior to leaf water status declining, were apparently independent of later stomatal closure in response to drought. These biochemical differences can have implications in regulating transpiration, since <i>Eutrema</i> reduced whole plant water use very early (Day 3) while this occurred later (Day 6 onwards) in <i>Arabidopsis</i>. <i>Arabidopsis</i> provides a promising model to evaluate the mechanisms responsible for stress-induced growth inhibition under the mild/moderate soil drying that crop plants are typically exposed to.</p>
Suggested Reviewers:	<p>THIERRY SIMONNEAU thierry.simonneau@inra.fr</p>
	<p>Bertand Muller muller@supagro.inra.fr</p>
	<p>Radka Vankova UEB Prague Vankova@ueb.cas.cz</p>
	<p>Vicent Arbona UJI, Castellon arbona@uji.es</p>

[Click here to view linked References](#)

**Distinctive phytohormonal and metabolic profiles of *Arabidopsis thaliana* and *Eutrema  
salsugineum* under similar soil drying**

Carla Pinheiro<sup>1,2,\*</sup>, Elizabeth Dickinson<sup>3</sup>, Andrew Marriott<sup>3</sup>, Isa C. Ribeiro<sup>1</sup>, Marta Pintó-  
Marijuan<sup>1,5</sup>, Carla António<sup>1,3</sup>, Olfa Zarrouk<sup>1</sup>, Maria Manuela Chaves<sup>1</sup>, Ian C. Dodd<sup>6</sup>, Sergi  
Munné-Bosch<sup>5</sup>, Jane Thomas-Oates<sup>3</sup>, Julie Wilson<sup>3,4#</sup>.

<sup>1</sup> Instituto de Tecnologia Química e Biológica, Universidade NOVA de Lisboa, Av. da  
República, EAN, 2781-901 Oeiras, Portugal

<sup>2</sup> DCV - Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa, 2829-516  
Caparica, Portugal

<sup>3</sup> Department of Chemistry, University of York, Heslington, York YO10 5DD, United  
Kingdom

<sup>4</sup> Department of Mathematics, University of York, Heslington, York YO10 5DD, United  
Kingdom

<sup>5</sup> Department of Evolutionary Biology, Ecology and Environmental Sciences, Facultat de  
Biologia, Universitat de Barcelona, Avinguda Diagonal 643, 08028 Barcelona, Spain

<sup>6</sup> The Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom

\* Corresponding author: [pinheiro@itqb.unl.pt](mailto:pinheiro@itqb.unl.pt)

# Corresponding author: [julie.wilson@york.ac.uk](mailto:julie.wilson@york.ac.uk)

Running title: ***Arabidopsis* and *Eutrema* responses to soil drying**

## Abstract

Although plants perceive and respond to soil drying via a series of concurrent physiological and molecular events, drought tolerance differs greatly within the plant kingdom. While *Eutrema salsugineum* (formerly *Thellungiella salsuginea*) is regarded as more stress tolerant than its close relative *Arabidopsis thaliana*, their responses to soil water deficit have not been compared. To ensure a similar rate of soil drying for the two species, daily soil water depletion was controlled to 5-10 % of the soil water content. While partial stomatal closure occurred earlier in *Arabidopsis* (Day 4) than *Eutrema* (from Day 6 onwards), thereafter both species showed similar stomatal sensitivity to drying soil. Nonetheless, both targeted and untargeted metabolite analysis showed larger responses in *Arabidopsis* in both early/mild drought (Days 1, 3, 5 – no significant change in leaf relative water content, RWC) and late/severe drought (Day 12 – circa 80 % decrease in leaf RWC). *Arabidopsis* (but not *Eutrema*) showed early peaks in foliar abscisic acid (ABA), jasmonic acid (JA) and salicylic acid (SA) contents. *Arabidopsis* showed greater metabolic adjustment than *Eutrema* during both early drought stress (428 versus 35 variables significantly changing) and severe drought (607 versus 171 variables significantly changing). Different sugar profiles between species were accompanied by opposing patterns in the bioactive cytokinin profile responses. The distinctive metabolic responses of each species during early drought, which occurred prior to leaf water status declining, were apparently independent of later stomatal closure in response to drought. These biochemical differences can have implications in regulating transpiration, since *Eutrema* reduced whole plant water use very early (Day 3) while this occurred later (Day 6 onwards) in *Arabidopsis*. *Arabidopsis* provides a promising model to evaluate the mechanisms responsible for stress-induced growth inhibition under the mild/moderate soil drying that crop plants are typically exposed to.

Keywords: bioactive cytokinins; rewatering; redox state; stomatal conductance; unsupervised multivariate analysis

## Introduction

In view of climate change, a major goal for the plant biology community is to understand the mechanisms that allow some plants to withstand drought or hot weather. Knowledge of how plants survive and reproduce in challenging environmental conditions can allow novel targets to be tested in crop-breeding programs. The well-known model species *Arabidopsis thaliana* provides information that can be applied to crop systems (Piquerez *et al.*, 2014; Gilliam *et al.*, 2017). Using the Columbia accession (Col-0) and its mutants has allowed many stress regulatory and responsive pathways to be deciphered (Koornneef and Meinke, 2010; Osakabe *et al.*, 2014), although its stress resilience has not been fully established. Despite wide ecotypic variation (Montesinos-Navarro *et al.*, 2011; Clauw *et al.*, 2016), *Arabidopsis* is not expected to cope well in extreme environments (Zhu *et al.*, 2015). Instead, *Arabidopsis* relatives such as *Eutrema salsugineum* have been proposed as stress-tolerant models (Orsini *et al.*, 2010; Zhu *et al.*, 2015). *Eutrema* seems prepared for stress, as its stress-related genes are upregulated in comparison to *Arabidopsis* even when grown under optimal conditions (Taji *et al.*, 2004; Gong *et al.*, 2005). As in *Arabidopsis*, *Eutrema salsugineum* ecotypes from different geographical regions show significant genetic variation (Lee *et al.*, 2016). However, physiological and metabolic responses of *Arabidopsis* and its stress tolerant relatives to soil water deficit have not been directly compared.

Physiological responses to water deficit are modulated by the intensity, duration, and rate of progression of imposed drought (Pinheiro and Chaves, 2011). Extensive research on the stomatal regulation of water loss demonstrates a trade-off between carbon assimilation, efficient water use and leaf cooling capacity (Chaves *et al.*, 2016). Plants can be grouped according to whether they avoid heat (keeping their stomata open for longer) or use water efficiently (closing their stomata sooner, a typical drought-avoidance strategy). However, if plants can avoid the deleterious effects of heat by keeping their stomata open for longer, while maintaining a favourable water status by extracting more water (e.g. by having deep roots), this strategy benefits carbon uptake in addition to the cooling effect. Under drought, *Arabidopsis* Col-0 closes its stomata at higher soil moisture levels than other *Arabidopsis* genotypes (Meyre *et al.*, 2001). The two well-studied ecotypes of *Eutrema*, Shandong and Yukon, can grow under limited soil water availability (Xu *et al.*, 2014; Macleod *et al.*, 2015), but their drought performance, relative to *Arabidopsis*, is unknown.

The two plant species seemingly have distinct water consumption strategies, although it may

be difficult to separate species *versus* accession variation. Arabidopsis (Col-0) had relatively higher total transpiration than Eutrema (Shandong) under non-challenging conditions, which was related to its higher relative growth rate (Orsini *et al.*, 2010). Salinity decreased transpiration to a larger extent in Arabidopsis than Eutrema. In addition to these different water consumption strategies, Eutrema and Arabidopsis also had different biochemical composition under non-challenging growth conditions, with foliar sucrose and glucose content higher in Eutrema, while the hormones salicylic acid (SA) and jasmonic acid (JA) were higher in Arabidopsis (Arbona *et al.*, 2010; Pilarska *et al.*, 2016). Furthermore, Eutrema expressed more stress and defence genes than Arabidopsis under non-challenging conditions, which is described as stress priming (e.g. Zhu *et al.*, 2015; Lee *et al.*, 2016). It is uncertain whether these biochemical differences regulate differences in transpiration, and consequently different rates of soil water depletion.

However, the metabolic features associated with the initial stages of soil drying are not clear. In Arabidopsis, soil drying partially closes the stomata well before any decrease in carbon assimilation rate (Hummel *et al.*, 2010; Bechtold *et al.*, 2016) or any significant increase in foliar abscisic acid (ABA) content (Bechtold *et al.*, 2016). ABA is described as the main driver controlling plant performance under limited water availability since it induces stomatal closure, but more comprehensive recent studies demonstrated that most of the plant hormones are involved in stress signalling (Müller and Munné-Bosch, 2015). In addition, during the very early stages of water limitation, effects on carbon metabolism (CO<sub>2</sub> assimilation, and sucrose and starch formation and allocation) may be decoupled from stomatal closure (Pinheiro *et al.*, 2011; Bechtold *et al.*, 2016). Many players are involved in stress perception and signal transduction leading to large alterations in carbon metabolism, and in the transcription program (Golldack *et al.*, 2014; Urano *et al.*, 2017). The metabolic balance between several molecules triggers adjustment mechanisms, and when several thresholds are achieved, physiological responses to drought occur (Pinheiro *et al.*, 2011). The integration of multiple environmental signals by sugars, hormones, and reactive oxygen species (ROS) adjusts plant growth and determines whether plants survive or perish under given environmental conditions (Pinheiro and Chaves, 2011; Osakabe *et al.*, 2014). The precise chain of events is not yet defined, and although some pathways and interactions are understood, others are more elusive (Rivas-San Vicente and Plasencia, 2011; Munné-Bosch and Müller, 2013; Ruan, 2014; Considine and Foyer, 2014; de Ollas and Dodd, 2016). Although recent reports highlight that stomatal closure is one of the initial events in response

to soil drying, many other metabolic adjustments also take place.

This work aimed to explore the metabolic adjustments prior to significant stomatal closure in *Arabidopsis* (Col-0) and *Eutrema* (Shandong) responding to slowly-imposed soil water deficit. Our working hypothesis is that *Arabidopsis* and *Eutrema* show distinctive responses to progressive and slow soil drying. In addition, untargeted analysis of LC-MS metabolite data was used to detect similarities and differences between these two species.

## Materials and Methods

*Arabidopsis thaliana* (Col-0) and *Eutrema salsugineum* (Shandong) seeds were soaked and stratified at 4 °C for 4 or 14 days, respectively. *Eutrema salsugineum* is the current designation of *Thellungiella salsuginea* (Integrated Taxonomic Information System on-line database, [www.itis.gov](http://www.itis.gov); The International Plant Names Index, [www.ipni.org](http://www.ipni.org)). Seeds were then transferred to pots (300 mL) containing a 1:1 mixture of coarse sand and peat (Shamrock). Plants were grown under controlled conditions, under a 12 h photoperiod, temperatures ranging from 20 to 24 °C, with a 60-70 % relative humidity and photosynthetically active radiation (PAR) of 250-300  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (SON-T Agro 400w, Phillips). Plants were watered every day with demineralized water to 85 % of soil water content (SWC). SWC was monitored daily and is defined as:  $\text{SWC} = [(\text{pot weight} - \text{pot weight with totally dried substrate}) / [(\text{pot weight at drained capacity} - \text{pot weight with totally dried substrate})] \times 100$ . Drought stress treatments were imposed when plants had 8 to 10 fully expanded leaves (40 days for *Eutrema* and 36 days for *Arabidopsis*) and had covered the surface of the pots (thereby minimising evaporation from the soil). During the experiment plant growth increased, on average by 2.9 g fresh weight (FW) for *Arabidopsis* and 2.5 g FW for *Eutrema*, corresponding to less than 0.8 % error in estimating SWC (Fig. 1).

Preliminary drought experiments, in which water was withheld, showed faster soil water depletion and more rapid stomatal closure in *Arabidopsis* (supplementary Fig. S1). Similarly, higher transpiration rates of *Arabidopsis* were previously reported (Orsini *et al.* 2010). Stomatal conductance of the two species was differentially sensitive to soil drying (supplementary Fig. S1B and C). Within the 45-55 % SWC range, *Arabidopsis* showed greater stomatal closure than *Eutrema*, but below 40 % SWC both species showed similar stomatal sensitivity to soil water deficit and were severely affected by drought. However,



analysis of covariance demonstrating no significant species x SWC interaction, both species showed a similar relationship between % gs vs soil water content, with (supplementary Fig S1C).

To compare stress duration and intensity effects on plant responses, the rate of soil water depletion was controlled to 5-10 % of the SWC per day by pre-dawn irrigation (Fig. 1). Even when controlling the SWC, Arabidopsis consumed more water than Eutrema, as indicated by the greater divergence between SWC measured at maximum soil water deficit (symbols) and the SWC to which the pot was re-turned to pre-dawn ("stress" line in Fig 1). This greater water use of Arabidopsis was most prominent between Days 3 and 7.

Plants were harvested 0 (last day of watering), 1, 3, 5 and 12 days after the beginning of the assay, corresponding to 75 %, 66 %, 45 %, and 12 % SWC, respectively. Samples were also taken the day after re-watering (1 d). Six biological replicates were obtained at each time-point, except for Day 1 controls for which there were only five biological replicates, providing 65 samples of each plant species. At the beginning of the assay, the most recently expanded two-three leaflets were identified and used for physiological and water status measurements. For the biochemical analysis, and when analysing severe drought and early rewatering, only non-senescent leaflets were used, i.e. the younger leaflets. Samples for biochemical (hormone, carbohydrate, pigment and oxidative status) analysis were immediately frozen in liquid nitrogen and kept at -80 °C until further extraction and analysis. Samples for osmotic potential and for RWC were then collected.

#### ***Leaf conductance, water status and osmotic adjustment***

Stomatal conductance was measured 2-3 h after the beginning of the photoperiod in five plants per treatment using a portable gas exchange photosynthesis system coupled to a 6400-15 chamber (1 cm<sup>2</sup> diameter cuvette, Li-6400, Li-Cor, Lincoln, Nebraska, USA). Three to five measurements were made per plant on the most recently expanded leaf.

Leaf and root samples were taken 4 h after the beginning of the photoperiod. Leaf discs (3 mm diameter) and total roots were weighed to obtain fresh weight (FW), placed in darkened petri dishes containing distilled water for 2 h to fully hydrate, then re-weighed to obtain turgid weight (TW), and then dried at 80 °C for 48 h to obtain dry weight (DW). Leaf (LRWC) and root (RRWC) relative water content were calculated as:  $RWC = [(FW - DW) \times 100 / (TW - DW)]$ .

Leaf osmotic potential ( $\psi_s$ ) was evaluated from leaf disks (8 mm,  $n = 5-6$ ), frozen and stored at  $-80\text{ }^{\circ}\text{C}$ . The leaf osmotic potential was measured with an HR-33T dew point microvoltmeter and C-52 sample chambers (Wescor, Inc., Logan, UT, USA). The osmotic potential was adjusted to the LRWC to calculate the osmotic potential at full turgor (OP100), and the osmotic adjustment was calculated as previously described (Turner *et al.*, 2007).

#### ***Phytohormone quantification via LC-MS targeted analysis***

Freeze-dried shoots (50 mg) were used to extract and quantify the following hormones (Müller and Munné-Bosch, 2011): auxin (indole-3-acetic acid: IAA), gibberellins (GA1, 4, 9, 19, 20, 24), cytokinin (CK) compounds (trans-zeatin: Z; trans-zeatin riboside: ZR; 2-isopentenyl adenine: 2iP; isopentenyl adenosine: IPA; dihydrozeatin: DHZ; dihydrozeatin riboside: DHZR), and stress-related phytohormones (ABA; JA; SA; and ethylene precursor 1-amino-cyclopropane-1-carboxylic acid: ACC).

Extraction was performed in methanol solutions containing 1 % glacial acetic acid, using the following standards:  $d_5$ -IAA,  $d_6$ -2-isopentenyl adenine ( $d_6$ -2iP),  $d_6$ -IPA,  $d_6$ -ABA,  $d_5$ -JA,  $d_4$ -SA,  $d_4$ -ACC,  $d_2$ -GA1,  $d_2$ -GA4,  $d_2$ -GA9,  $d_2$ -GA19,  $d_2$ -GA20 and  $d_2$ -GA24;  $d_5$ -Z and  $d_5$ -ZR were used as standards for Z, DHZ, ZR, and DHZR. After adding 170  $\mu\text{L}$  of the extraction solution and 30  $\mu\text{L}$  of a solution containing 100 ppm of the standards in the same solvent, the materials were mixed in a vortex mixer for 5 s and exposed to ultrasound for 30 min, followed by centrifugation at 9,500  $g$  for 10 min. The supernatant was removed and the residue was washed twice with 100  $\mu\text{L}$  of the solvent solution. The supernatant and washes were combined and filtered through PTFE 0.22  $\mu\text{m}$  filter paper (Waters, Milford, MA) and 5  $\mu\text{L}$  aliquots were analysed using a UPLC-ESI-MS/MS (Acquity UPLC System from Waters, Milford, MA) and tandem MS/MS experiments were performed on an API 3000 triple quadrupole mass spectrometer (PE Sciex, Concord, Ont., Canada) using a HALO™ C18 column ( $2.1 \times 75\text{ mm}$ ,  $2.7\text{ }\mu\text{m}$ ) (Advanced Materials Technology, Inc. Wilmington, DE) and a binary mobile phase system composed of (A) water modified with 0.05 % glacial acetic acid and (B) acetonitrile modified with 0.05 % glacial acetic acid. Quantification was performed by preparing a calibration curve including each of the analysed compounds and calculating the compound/standard ratio using Analyst™ software (Applied Biosystems, Inc., Foster City, CA). The results were expressed on a dry weight (DW) basis.

#### ***Ascorbate oxidative status***

Ascorbate reduced and oxidized forms were determined by a plate-reader method (Queval and Noctor, 2007) with slight modifications. Briefly, lyophilised leaves (20 mg DW) were placed in a microcentrifuge tube with two tungsten balls and ground under liquid nitrogen in a Retsch MM300 Bead Mill Cell Disrupter (Retsch GmbH & Co Haan Germany). Subsequently, 1 mL of extraction buffer (6 % meta-phosphoric acid) was added, vortexed for 1 min and clarified by centrifugation at 10,000 g (10 min, 4°C). Finally, extracts were neutralized and adequately diluted before spectrophotometric readings on a 96 well quartz microplate (Hellma Hispania SL, Badalona, Spain). The levels of ascorbate (AscA) (reduced) and dehydroascorbate (DHA) (oxidized) were determined using ascorbate oxidase (AO) and dithiothreitol (DTT), respectively (Foyer *et al.*, 1983). AO specifically oxidizes all AscA in the sample. Therefore, the decrease in O.D. at 265 nm is related to AscA content. Alternatively, when the samples are incubated with DTT, DHA is reduced to AscA and the increase in O.D. is proportional to the initial DHA content. The ascorbate oxidative status was estimated as  $DHA/(DHA + AscA)$ .

#### ***Photosynthetic pigments quantification***

For pigment extraction, lyophilised leaf samples (15 mg DW) were placed in a microcentrifuge tube with two tungsten balls, ground under liquid nitrogen in a Retsch MM300 Bead Mill Cell Disrupter (Retsch GmbH & Co Haan Germany), and extracted with ice-cold 80 % acetone (v/v). After centrifuging at 6,500 g for 10 min at 4 °C, the supernatant was collected and the pellet was re-extracted with the same solvent until it was colourless. Then, supernatants were pooled and analysed spectrophotometrically. Specific absorption coefficients in 80 % acetone previously reported were used to quantify chlorophyll a, chlorophyll b and carotenoids (Lichtenthaler and Buschmann, 2001).

#### ***Extraction of water soluble carbohydrates and starch***

Water-soluble carbohydrates were extracted from freeze-dried leaf material following a chloroform:methanol method previously described (Antonio *et al.*, 2008). Briefly, 50 mg DW of leaf material was ground in liquid nitrogen and extracted with 250 µL ice-cold chloroform:methanol (3:7, v/v), vortex-mixed and incubated at -20 °C for 2 h. After incubation, samples were extracted twice with ice-cold water, and after centrifugation at 17,900 g at 4 °C for 10 min, the upper phases were collected and pooled. The combined supernatants containing the water-soluble carbohydrates were evaporated to dryness using a centrifugal concentrator (Savant SpeedVac Plus SC110A, Thermo Electron Corporation, Runcorn, UK). Samples

245 were reconstituted in 100  $\mu$ L water and centrifuged at 6,800  $g$  at 20  $^{\circ}$ C for 30 min, followed  
246 by LC-MS analysis.

247 For starch analysis, the pellet resulting from the chloroform:methanol extraction was washed  
248 twice with water. Ten volumes of water were added to the pellet, boiled for 3 min, and  
249 autoclaved at 130  $^{\circ}$ C for 1 h. After cooling, samples were incubated with 6 U  
250 amyloglucosidase (Roche Applied Science, Amadora, Portugal) for 2 h at pH 4.8 and 60  $^{\circ}$ C.  
251 Starch was quantified in the supernatant using a starch enzymatic quantification kit (n $^{\circ}$   
252 10207748035, R-Biopharm Aktiengesellschaft, Darmstadt, Germany) and by making use of  
253 the Hatterscheid and Willenbrink modification as previously described (Pinheiro *et al.*,  
254 2001).

### 255 *Untargeted LC-MS analysis of the water-soluble carbohydrate fraction*

256 Arabidopsis and Eutrema samples were analysed as separate cohorts. In each case, samples  
257 were randomized and run in batches of eight or nine with the injection of a pooled sample  
258 between batches for quality control (QC). LC-MS analyses were performed on a Dionex  
259 U3000 2D HPLC system coupled to a Bruker maXis UHR-Q-TOF MS with an ESI interface.  
260 Analytes were detected in the negative ion mode using the following MS parameters:  
261 capillary voltage, 4500 V; nebulizer gas, 2 Bar; drying gas, 8.0 L/min; drying temperature,  
262 200  $^{\circ}$ C, and collision energy, -10.0 eV. Mass spectra were acquired over the scan range  $m/z$   
263 50-1000. Chromatographic separation was carried out using a porous graphitic carbon (PGC)  
264 Hypercarb<sup>TM</sup> column (5  $\mu$ m, 100 mm  $\times$  4.6 mm; Thermo Electron, Runcorn, Cheshire, UK)  
265 at a flow rate of 600  $\mu$ L min<sup>-1</sup>. All samples were reconstituted with 500  $\mu$ L deionised water  
266 with a further 50-fold dilution in deionised water to prevent signal saturation and to minimise  
267 matrix effects. The sample injection volume was 20  $\mu$ L and the PGC column was used at  
268 ambient temperature (25  $^{\circ}$ C). The binary mobile phase was composed of (A) water modified  
269 with 0.1 % (v/v) formic acid (FA) and (B) acetonitrile modified with 0.1 % FA. The gradient  
270 elution was as follows: 0-4 min maintained at 2 % B; 4-7 min, 2 to 8 % B; 7-10 min 8-25 %  
271 B and maintained for 3 min, followed by column regeneration and re-equilibration: 13-19  
272 min, 25 to 40 % B; 19-19.5 min, 40 to 50 % B held for 1 min; 20.5-21 min 50 to 99 % B held  
273 for 2 min; 23-25 min 99 to 2 % B and maintained for 10 min. All solvents were purchased  
274 from Fisher Scientific except FA, which was purchased from Sigma Aldrich.

### 275 *Statistical analysis*

Raw LC-MS data were pre-processed using Progenesis QI (Nonlinear Dynamics, Newcastle Upon Tyne, UK). Mass spectra were aligned by retention time and normalized to the same total ion count before peak picking was performed to provide a matrix of potential metabolites for each observation, annotated by the accurate mass ( $m/z$  between 50 and 1000) and retention time (between 1 and 30 min) of the corresponding peak. In total, 53208 and 33032 peaks were recorded for Arabidopsis and Eutrema, respectively, and were used as variables in multivariate and univariate analyses.

When the Eutrema data were scaled to unit variance to allow smaller variables to contribute to the analysis, differences between batches became apparent, with the last two batches differing substantially from the rest (supplementary Fig. S2A). Liquid chromatography-mass spectra are often acquired batch-wise to allow necessary calibrations and cleaning of the instrument. However, this may introduce further sources of variation, such as differences in the conditions under which data for individual batches is acquired. Quality control (QC) samples are frequently employed to both judge and correct for this variation.

However, batch correction using the QC observations increased inter-batch variation as the change in observations between batches was often not well-represented by the change in corresponding QCs. Therefore, background correction for each variable was performed (Rusilowicz *et al.*, 2016; Wehrens *et al.*, 2016). This method identifies a background trend, using experimental observations as well as the QCs, with which to adjust the intensities. The run order for data collection was randomized, but by chance a disproportionate number of early-stress observations occurred in batch 3 and several late-stress observations in batch 4. With the exception of these two batches, which were combined, we used a separate trend for each batch, obtained as a moving median with a window width of 5 observations. The effectiveness of batch correction was assessed using the Bhattacharyya distance (Wehrens *et al.*, 2016). In addition, an outlier that dominated the variance after scaling was removed before calculating the trend. Control correction was also performed on each variable to remove differences due to growth. For each day of harvest, this was achieved by subtracting the median over the six control replicates from the corresponding variable in the water-stressed observations for that day. The Arabidopsis data showed no obvious differences between batches (supplementary Fig. S3), and therefore, batch correction was deemed unnecessary but control correction was performed to prevent differences due to growth from masking early-stress characteristics.

Principal components analysis (PCA) was used for unsupervised multivariate analysis with both unscaled data and after scaling to unit variance to prevent high content metabolites dominating the analysis. To identify patterns in metabolites over time, k-means cluster analysis was performed with the control-corrected time-series for both datasets. The obtained initial clusters were filtered using the sum of squared values to remove the time-series for metabolites that did not differ appreciably between drought and control observations, i.e. where all values in the control-corrected time-series were close to zero. Cluster analyses of the remaining time-series (with various values of  $k$ ) showed the largest cluster to consist of less interesting time-series and an iterative filtering process was used to reduce the number of time-series, leaving only those with the most interesting patterns. In each iteration, k-means clustering with  $k = 15$  was performed and the largest cluster removed before the next analysis. After four iterations, 46 time-series remained and were clustered using k-means with  $k = 9$ .

Univariate analyses were performed using the non-parametric Mann-Whitney U-test with Benjamini-Hochberg correction for multiple comparisons (Benjamini and Hochberg, 1995). Three-way group comparisons were carried out (early stress/late stress/rewatered and Days 1, 3 and 5 for each species) with one-way ANOVA and Tukey's honest significant difference (HSD) correction for multiple pairwise testing. Data correction methods were implemented using C code written in-house and statistical analyses were performed in the R platform, version 2.13.1 (R Core Team, 2016) or in Matlab (The MathWorks Inc., Natick, MA, USA).

Analysis of covariance (ANCOVA) discriminated possible species difference in stomatal sensitivity to drying soil.

## Results and discussion

### *Stomatal sensitivity to drying soil and plant water status*

Under well-watered conditions, stomatal conductance (gs) of both species exceeded  $0.11 \text{ mol m}^{-2} \text{ s}^{-1}$  (supplementary Fig S4A). Since gs of well-watered plants varied from day to day, gs of plants in drying soil was normalised according to the average well-watered values of each species. As the soil dried (Fig. 2), partial stomatal closure of Arabidopsis and Eutrema was detected on Days 4 and 6, respectively (Fig. 2). Within the 45-55 % SWC range, Arabidopsis showed greater stomatal closure than Eutrema, but below 40 % SWC both species showed

similar stomatal sensitivity to soil water deficit and were severely affected by drought. Stomatal conductance responded sluggishly to re-watering, with limited recovery (supplementary Fig S4A). Across the entire experiment, both species showed a similar relationship between % gs vs soil water content, with analysis of covariance demonstrating no significant species x SWC interaction (supplementary Fig S4B). Thus, both species showed similar stomatal sensitivity to drying soil.

Initial stomatal closure was not associated with decreased leaf water status, i.e. lower cell volume did not trigger early stomatal closure (Sack *et al.*, 2018). On imposing soil water deficit, no significant differences in *Eutrema* leaf (and root) RWC were detected until Day 5 (supplementary table S2). In *Arabidopsis*, leaf RWC transiently decreased on Day 3 (supplementary table S1). Although statistically significant (at the 95% confidence level), its small magnitude (~4%) could be within the method error or due to daily fluctuations.

In contrast to plant water status, the water consumption patterns changed very early on, but were not temporally correlated with stomatal closure. Compared with its well-watered control, *Eutrema* started to lose less water from Day 3 onwards (3 days before any significant stomatal closure), as indicated by the slope of the soil RWC% line for plants in drying soil (Fig. 1). In contrast, *Arabidopsis* started to use less water on Day 6 onwards (two days after partial stomatal closure occurred). This suggests that earlier growth inhibition of *Eutrema*, decreased whole plant water loss independent of changes in plant water status.

By Day 12, leaf RWC of both species had declined to very low values (< 20 %) and leaflets selected for water status measurements (those most recently expanded at the onset of the assay) were severely wilted and exhibited senescence symptoms. Lower leaf chlorophyll fluorescence (Fv/Fm) and lower chlorophyll a content indicated photo-inhibition and/or leaf senescence (Kalaji *et al.*, 2016).

Despite the severity of the stress imposed, root water status of both species recovered within 24 h of re-watering. Root RWC of *Eutrema* was similar to those of the well-watered controls, while the root RWC of *Arabidopsis* was ~90 % of that of the controls. However, leaf RWC remained low, only ~50 % and ~40 % of the well-watered control values in *Eutrema* and *Arabidopsis* respectively (supplementary tables S1 and S2). In addition, Fv/Fm tended to increase in *Eutrema*, but values were unaffected in *Arabidopsis* (supplementary tables S1 and S2).



Traditionally, it has been argued that only resurrection plants can survive such severe drought, i.e. recover from leaf RWC values below 20% (Dinakar and Bartels, 2013). Since leaf RWC was determined in the most recently expanded leaves at the beginning of the assay (see Material and Methods), these older leaves were severely wilted and senescent after 12 days, while younger leaves visually maintained turgor. Several reports indicate that *Arabidopsis* Col-0 plants are able to recover from severe drought, with 30% of Col-0 plants surviving exposure to 15% SWC and severe wilting (Sun *et al.* 2013) while 20% of severely wilted Col-0 plants survived SWCs < 20% (Zhao *et al.* 2016). Moreover, Col-0 plants with 40-50% leaf RWC recovered from drought (Meyre *et al.* 2001; Tran *et al.* 2007; Kosma *et al.* 2009; Koffler *et al.* 2014) while some plants recovered from 20% leaf RWC although the survival percentage was very low ( Lü *et al.* 2012; Nguyen *et al.* 2016). In contrast to *Arabidopsis*, *Shandong* was able to recover from drought if the leaf RWC declined to 50%, but not 30% (Dedrick 2007). Since our measurements were made only 1 Day after rewatering and no plants were available to evaluate long-term recovery, irreversible damage cannot be ruled out.

As small changes in soil water content (10-15 %) affect not only leaf conductance but also plant metabolism (Davies *et al.*, 1990; Pinheiro *et al.*, 2011), both untargeted metabolite analysis and targeted metabolite/biochemical analysis aimed to determine the impact of gradually declining soil water availability on leaf metabolism. This approach aimed to detect species differences in metabolism when plant water status was not affected (up to Day 5).

### *Untargeted metabolite analysis*

The responses to soil water depletion in *Arabidopsis* and *Eutrema* were analysed via untargeted LC-MS, making use of the water-soluble fraction. After batch correction of the *Eutrema* data, PCA of the control corrected and scaled data grouped according to drought-stress duration for both species (Fig. 3). Moreover, PCA of unscaled data showed that most of the variance is due to large differences between early-stress (Days 1, 3 and 5) and late-stress (Days 12 and 13) observations. Statistical separation of late-stress effects was not related to differing sample water content, since comparable dry weights were used and the resulting data normalised before statistical analysis.

When considering only the early-stress observations, the PCA scores plot shows clear



grouping of the observations by stress duration for both plant species (Fig. 4). Distinctive metabolic signatures were obtained even for early days with limited soil drying (< 20 % change in SWC at Day 3). The PCA loadings identified variables that most influenced the separation between Days 1, 3 and 5, and early- and late-stress observations. In addition, an iterative k-means algorithm filtered out the largest clusters to leave those comprising more unusual, and potentially more informative, patterns (supplementary Fig. S5). Hierarchical clustering with the 46 time-series selected by the k-means analysis (Fig. 5; supplementary Fig. S6) allowed the similarities (or differences) between the associated metabolites to be visualised.

### *Severe drought causes larger metabolic alterations in Arabidopsis than in Eutrema*

Late-stress markers for both *Arabidopsis* and *Eutrema* included peaks that were identified as the carbohydrates sucrose and raffinose, by comparison with authentic standards of these molecules. Sucrose significantly increased and raffinose significantly decreased ( $p < 0.001$ ) in late stress (Day 12) and on re-watering (Day 13). A significant decrease was found for features with  $m/z$  values of 341 and 387, most probably a hexose disaccharide. A feature with  $m/z$  711, also decreasing significantly, is tentatively assigned to stachyose, known to co-elute with raffinose (Antonio *et al.*, 2008). Sucrose (detected in a range of ionic forms) observed at high levels in the leaf blade tissue (Table 1) was not unexpected. Drought stress upregulated sucrose synthesis in different resurrection plants (Peters *et al.*, 2007; Whittaker *et al.*, 2007; Gechev *et al.*, 2013) as well as in herbaceous and woody plants (e.g Antonio *et al.*, 2008; Pinheiro and Chaves, 2011; Granda and Camarero, 2017). Although stress downregulated raffinose synthesis in several resurrection plants (Muller *et al.*, 1997; Moyankova *et al.*, 2014), raffinose is typically described as being upregulated under stress (Elsayed *et al.*, 2014), including in *Arabidopsis* (Taji *et al.*, 2002). Soil water deficit significantly ( $p < 0.00001$ ) decreased two co-eluting features (with  $m/z$  191 and  $m/z$  405) in both plant species. The feature with  $m/z$  191 was assigned to citric acid, following tandem mass spectrometry ( $MS^2$ ) analysis and comparison of the fragmentation pattern in both METLIN ([www.metlin.scripps.edu](http://www.metlin.scripps.edu)) and PRiME ([www.prime.psc.riken.jp](http://www.prime.psc.riken.jp)) metabolomics databases. The co-eluting feature at  $m/z$  405.0019 on  $MS^2$  produced a single fragment at  $m/z$  191.0185, that was tentatively assigned as the  $[2M-2H+Na]^-$  charge-sharing dimer of citric acid (accurate mass 405.0287). Univariate analyses (after multiple test correction) indicated that

607 variables significantly ( $p < 0.0001$ ) differed between late-stress observations and controls in Arabidopsis, in comparison to just 171 in Eutrema, suggesting that Arabidopsis more extensively adjusts its metabolism. An alternative view is that larger changes in Arabidopsis indicate less active metabolism, since metabolites accumulate because the plant has no capacity to use them.

In the cluster analysis, three clusters tend to decrease over time, including the response of raffinose (supplementary Fig. S5C, S5D, S5G), which was more extreme in Arabidopsis than Eutrema, therefore occurring in a different cluster. Severe drought stress decreased the levels of raffinose in lupins, although this was preceded by a transient increase during early stress (Antonio *et al.*, 2008; Pinheiro *et al.*, 2011). Although the different ionic forms of citric acid from both Arabidopsis and Eutrema group together in cluster D, a difference in the trend between the two different plant species can be seen, with Eutrema showing an early increase before the overall decrease. Citric acid decreased in response to late and severe drought, as previously observed in lupin and Eutrema (Pinheiro *et al.*, 2004; MacLeod *et al.*, 2015). The final two clusters (Fig. S5H and S5I) show the response profiles of (unknown) compounds that are significantly greater than or lower than the controls throughout the time-series, notably all from Arabidopsis, and are good candidates for further studies.

In contrast, four clusters tended to increase rapidly in late drought; the scale of the response accounts for the difference between these four clusters. They mostly comprise the differing ionic forms of sucrose. In Arabidopsis, unknown compounds with  $m/z$  133 and  $m/z$  288 exhibited a very similar pattern to sucrose (supplementary Fig. S5A, S5B, S5E and S5F). The most extreme responses result in separate clusters consisting of just one or two observations (Fig. S5E-F). For each sucrose ionic species, the response for Days 12 and 13 is more extreme for Arabidopsis than for Eutrema. In both plant species, a further unknown with  $m/z$  195 also clusters with sucrose, and re-watering causes a greater response than during late stress.

### ***Severe drought causes larger biomass reduction in Eutrema than in Arabidopsis***

Although severe drought decreased the biomass of both species, Arabidopsis (22% decrease) was less sensitive than Eutrema (38% decrease) (supplementary tables S1 and S2). The mechanisms that limit biomass accumulation are poorly understood (Pinheiro and Chaves,

2011; Skirycz *et al.*, 2011). Under drought, the higher availability of sugars indicates that CO<sub>2</sub> assimilation is not limited as much as growth, with carbon being available but plants unable to use it, termed “sink limitation” (Wiley and Helliker 2012; Granda and Camarero, 2017). This also supports the concept of passive accumulation. On the other hand, higher sugar content may reflect their use in osmoregulation, maintaining cell integrity and providing readily available carbon to resume growth (active reserve storage concept; Granda and Camarero, 2017). Although osmotic adjustment was detected under severe drought and rewatering in *Eutrema* (supplementary table S2), it was only detected in *Arabidopsis* on rewatering (supplementary table S1). The growth reduction was accompanied by starch remobilization, supporting the hypothesis of carbon reserve reallocation. A regulatory mechanism that integrates carbon availability and its use within the plant (Smith and Stitt, 2007; Pinheiro and Chaves, 2011) partitions photoassimilates to other biochemical pathways (than growth) to withstand severe drought and/or resume growth whenever possible. To determine whether sucrose accumulation represents an active or passive process, it would be necessary to determine if and how carbon limits growth (Wiley and Helliker 2012). A better understanding of these mechanisms is crucial to select genotypes with more stable growth under stress. In that sense, a favourable ideotype will depend on where the plant is to be grown. Higher survival, largely due to conservative water consumption can be the most relevant selection criterion in arid or semi-arid regions. On the other hand, in moderate climates with milder droughts, plant production can be boosted if stress has little impact on growth (Skirycz *et al.*, 2011; Tardieu, 2012). Higher stomatal conductance is a positive trait when plants are under moderate/mild drought since it favors growth maintenance (Tardieu, 2012). In that scenario, *Arabidopsis* can provide a suitable model for biomass production under moderate drought.

#### ***Severe drought decreased ascorbate content of both species***

Under severe stress, some parameters, including ascorbic acid (AscA), leaf chlorophyll fluorescence (Fv/Fm) and chlorophyll a (Chla), have similar patterns in the two species. Lower Fv/Fm indicates a lower photochemical harvest, with a larger proportion of photons being diverted to non-photochemical quenching (heat and ROS production). Although two hormones (IAA and SA) are proposed to up-regulate ROS production (Rivas-San Vicente and Plasencia, 2011; Considine and Foyer, 2014; Khokon *et al.*, 2017), severe drought

significantly decreased SA content but did not alter IAA content. Thus, these hormones are unlikely to promote ROS accumulation. Water deficit has variable effects on carotenoid content (Koffler *et al.*, 2014; Uarrota *et al.*, 2018), but we did not detect quantitative alterations. However, decreased chlorophyll a content indicates that chlorophyll degrades faster than carotenoids (Lichtenthaler and Buschmann, 2001). A higher carotenoid to chlorophyll content can favour photo-protection per amount of light received. On the other hand, non-photochemical quenching via carotenoids requires ascorbate for correct function (Koffler *et al.* 2014). Severe drought significantly decreased ascorbate content (43% in *Eutrema*; 24% in *Arabidopsis*), which could have compromised such quenching. Noctor *et al.* (2014) state that ascorbate content is only significantly decreased by drought when stress-induced senescence processes are activated. Although the sampled leaves did not show visible symptoms of senescence, their ascorbate levels suggest senescence programs were already activated. Under drought, both *Arabidopsis* Col-0 and Col-0 mutants with lower ascorbate content show senescence symptoms (Koffler *et al.*, 2014), with some mutant leaves showing necrosis. Rewatering further decreased the ascorbate content (55% in *Eutrema*; 52% in *Arabidopsis*), indicating the senescence program is still active. Changes in ascorbate reduction status can also modulate signalling pathways, affecting stress-response mechanisms (Considine and Foyer, 2014).

### *Arabidopsis and Eutrema are metabolically distinct*

To characterize in more detail the responses to soil water depletion in *Arabidopsis* and *Eutrema*, various biochemical parameters (Table 2) were measured during early drought. Some metabolites showed minimal (< two-fold) differences between species, while starch, JA and ZR were more abundant in *Arabidopsis*, and IAA and DHA were more abundant in *Eutrema* (supplementary tables S1 and S2). Distinctive phytohormone profiles under non-challenging conditions were previously reported (Arbona *et al.*, 2010; Pilarska *et al.*, 2016).

To remove the effects of differential growth between species, data were control-corrected by subtracting the median control value from the measurements for each day. PCA analysis with all biochemical parameters for both species (supplementary Fig. S7) showed the greatest source of variance to be the separation of late/severe drought and re-watered (RW) observations, as in the untargeted analyses. Without variable scaling, loadings plots showed a large influence of the variables with the greatest mean values (leaf RWC, osmotic potential

(OP) and starch) in the total variance. After scaling to unit-variance, the separation of late stress/re-watered observations is still seen along the first principal component, although accounting for far less of the total variance. In *Arabidopsis*, variables from re-watered samples were closer to those from early-day observations. In *Eutrema*, the difference between late stress and re-watering is only apparent along the second component, which represents less variance and more similar metabolic status. These findings suggest: 1) *Arabidopsis* responds faster to soil water availability; and/or 2) *Eutrema* requires prolonged stimulus to reprogram its metabolism. However, whole plant water use of *Eutrema* is more conservative than *Arabidopsis* (with soil drying decreasing water use after 3 and 6 days respectively – Fig 1) in spite of an opposite stomatal response (with soil drying decreasing  $g_s$  after 4 and 6 days in *Arabidopsis* and *Eutrema* respectively – Fig. 2). Thus vegetative growth and stomatal closure seem independently regulated, with *Eutrema* reacting faster to soil water availability and *Arabidopsis* requiring prolonged stimulus. The “optimistic” strategy of *Arabidopsis* Col-0 maintains biomass production under mild stress and/or under deficit irrigation (Skirycz *et al.*, 2011). An alternative hypothesis could be that *Eutrema* slows its metabolism much earlier while *Arabidopsis* reprograms metabolism in a different way. It will be important to determine whether growth is maintained, both above and below ground, and if reserves are reallocated.

#### *Eutrema* responds with small changes to early drought

In both *Arabidopsis* and *Eutrema*, inspection of the PCA loadings showed that many variables contribute to the separation of each of the early stress days (Fig. 4). Thus metabolic separation between sampling dates is due to the cumulative changes arising from small contributions of many metabolites. However, the two species react differently to similar decrease in the soil water availability. More metabolites responded to early drought stress in *Arabidopsis*, with 428 variables showing statistically significant differences between Days 1, 3 and 5 ( $p < 0.01$ ; 36 with  $p < 0.001$ ) in comparison to 35 in *Eutrema* ( $p < 0.01$ ; 4 with  $p < 0.001$ ). However, none of the variables that consistently differed between the early days corresponded to those identified as late-stress markers (such as sucrose), showing different metabolism during early and late drought.

The larger changes in *Arabidopsis* suggest different metabolic strategies to deal with the progressive decline in soil water availability. This is consistent with greater stomatal closure

of *Arabidopsis* than *Eutrema* on Day 5 (Fig. 2), supporting a drought avoidance strategy for *Arabidopsis*. Partial stomatal closure can limit carbon assimilation and carbon availability for respiration and growth (Pinheiro and Chaves, 2011). Acclimation of *Arabidopsis* to optimise carbon use (Smith and Stitt, 2007) would increase carbon storage (e.g. via changes in starch synthesis and turnover) and adjust the growth rate. It could be that the changing conditions did not achieve the threshold required to induce the acclimatory response as, although stomata were starting to close, plant water status was not yet affected. A similar rationale can be used for *Eutrema* although its perception as a drought avoider (MacLeod *et al.*, 2015), suggests a different soil water availability threshold for acclimation. Transpiration data indicate more conservative water use in *Eutrema* than *Arabidopsis* (Fig. 1) although *Arabidopsis* had greater stomatal sensitivity to drying soil (Fig. 2). Together, these data suggest species differences in regulating water consumption, implying distinct integration of environmental signals to limit vegetative growth in *Eutrema* and induce stomatal closure in *Arabidopsis*

#### *Species-dependent hormonal responses during early stress*

ABA, JA, SA and GA profiles clearly discriminated the plant species between Days 1 and 5 (Table 3; Fig. 5 and supplementary Fig. S8). Despite daily irrigation to ensure a similar rate of soil drying in the two species, soil water deficit increased foliar ABA content of *Arabidopsis*, but not *Eutrema*, on Day 5 (Fig. 6). Although daily irrigation increases leaf water status and decreases ABA accumulation of plants exposed to reduced soil water availability (Puértolas *et al.*, 2017), significantly higher water consumption of *Arabidopsis* between Days 3 and 7 (Fig. 1) enhanced foliar ABA accumulation, potentially mediating stomatal closure. Nevertheless, temporal decoupling of foliar ABA accumulation from stomatal closure (Pinheiro *et al.*, 2011; Bechtold *et al.*, 2016) suggests that ABA quantification at the guard cell level (Harris and Outlaw, 1991) is needed to better understand the regulation of stomatal conductance. Alternatively, direct hydraulic regulation of stomatal conductance (that was not detected in RWC measurements), or water-deficit stimulation of localised foliar ABA accumulation (that was not detected in bulk leaf ABA measurements) provide alternative hypotheses for stomatal closure.

Also, increased JA content may stimulate stomatal closure (Daszkowska-Golec and Szarejko, 2013), either independently or in association with ABA accumulation (de Ollas and Dodd,



2016). Foliar JA content transiently increased on Day 3 only in Arabidopsis, preceding increased ABA accumulation on Day 5 (Fig. 6, supplementary Fig. S8). Transient increases in foliar JA accumulation preceded ABA accumulation in *Solanum lycopersicum* leaves (Muñoz-Espinoza *et al.*, 2015) and Arabidopsis (Arbona *et al.*, 2010). Thus, transient JA accumulation may be necessary to induce ABA accumulation thereby contributing to stomatal closure.

Similarly to JA, SA content transiently increased on Day 3 in Arabidopsis (Fig. 6). In Arabidopsis, SA promotes ROS production and accumulation, and activates S-type anion channels in guard cells involved in stomatal closure (Khokon *et al.*, 2017). SA-mediated stomatal closure is considered to be ABA-independent, but a positive cross-talk is also accepted (Rivas-San Vicente and Plasencia, 2011; Miura and Tada, 2014). On the other hand, SA has also been proposed to modulate redox homeostasis, by regulating antioxidant enzymes (Rivas-San Vicente and Plasencia, 2011).

In *Eutrema*, changes in leaf RWC and ABA occurred after Day 5, with foliar ABA accumulation in *Eutrema* occurring below 45 % SWC. Species differences could be associated with the osmotic potential (OP) and the redox state regulation, as significant changes were observed in *Eutrema*, but not in Arabidopsis (Fig. 7 and supplementary Fig. S8). Decreased OP in *Eutrema* at Day 3 may maintain turgor, thereby removing the stimulus for ABA synthesis (Sack *et al.*, 2018). The opposing trends seen in AsCA and DHA for Days 3 and 5 in *Eutrema* may induce signalling patterns that prevented ABA accumulation. In Arabidopsis, ABA increased at Day 5, but there were no significant changes in AsCA or DHA until Day 5. Diminished stomatal closure of *Eutrema* may be related to its limited metabolic response to soil drying (Fig. 2), since hormonal activation of stomatal closure may require specific metabolic thresholds to be achieved. On the other hand, since *Eutrema* limits whole plant water consumption earlier than Arabidopsis, its limited metabolic response can be related to slower metabolism, reflecting stress avoidance (Tardieu, 2012). Altered GA metabolism also supports the hypothesis that Arabidopsis responds differently than *Eutrema* to soil water availability. Two precursors of the bioactive GA4 (GA24, GA9; Fig. 6&7, Table 3) showed altered profiles in Arabidopsis but not in *Eutrema*; with increased GA24 and GA9 contents at Day 5 indicating GA4 deactivation, a growth inhibitory signal.

Despite similar stomatal response to drying soil, phytohormonal responses substantially differed between the two species. The multiplicity of possible stomatal effectors suggests that

the most parsimonious stomatal regulation is via leaf hydraulics (Tardieu, 2016), yet until Day 5 there was scant evidence that soil drying altered leaf water status, at least in *Eutrema*. Redundancy in stomatal regulation between closely-related species may confer an evolutionary advantage under specific environmental conditions.

#### *Severe drought and rewatering induce opposite ACC and CK profiles in the two species*

With the exception of SA, hormone responses to soil drying are quite distinct in the two species (Table 2). Severe drought increased content of the ethylene precursor ACC by 70 % in *Eutrema*, but had no effect in *Arabidopsis*, suggesting ethylene-independent stomatal closure as both species showed similar stomatal sensitivity to drying soil. In contrast, re-watering *Eutrema* returned ACC levels to well-watered values, while profoundly increasing ACC content in *Arabidopsis*. Enhanced foliar ethylene emission following re-watering has been attributed to additional root ACC export (Gomez-Cadenas *et al.*, 1996) and may be involved in citrus leaf abscission. Moreover, assuming these increases in foliar ACC content are coincident with enhanced ethylene emission, they may also be involved in growth regulation.

Several CK species including ZR and 2-iP, long distance translocation forms of CKs (Kieber and Schaller, 2014), as well as the 2-iP precursor IPA accumulated in *Arabidopsis* but not in *Eutrema* during late stress (Fig. 8; supplementary Fig. S9). In contrast, re-watering returned content of these CKs to well-watered values in *Arabidopsis*, while stimulating their accumulation in *Eutrema*. IPA and 2-iP are precursors of Z, one of the most active CK forms (Jameson, 2017). However, the mobilization (metabolism and/or transport) of these CKs in *Arabidopsis* was not reflected in higher Z levels. Decreased levels of bioactive CKs due to severe and prolonged drought stress have been associated with better performance under drought, in mutants with decreased levels of bioactive CKs achieved via overexpression of *CKX* genes or by inactivating *IPT* genes (Ha *et al.*, 2012). Since these mutant lines show reduced growth under optimal conditions, it can be argued that their water requirements are lower than those of the WT. However, while lower evapotranspiration is described for some *CKX* mutants (Farber *et al.*, 2016), *ipt* mutants show similar water consumption (Nishiyama *et al.*, 2011). On the other hand, senescence-induced *IPT* overexpression, maintained bioactive CK content as the soil dries (Rivero *et al.*, 2007; Xu *et al.*, 2017), without reducing growth (Rivero *et al.*, 2007). Nevertheless, re-watering increased bioactive CKs in these



drought-tolerant transgenics (Rivero *et al.*, 2007). Although differential CK profiles may mediate plant drought stress responses, the two species showed similar stomatal sensitivity to soil drying and re-watering, suggesting CK-independent stomatal regulation.

## Conclusions

Arabidopsis and Eutrema responded physiologically (stomatal closure) and metabolically with temporal differences to slowly imposed drought. Following soil drying (Days 1 to 5), Arabidopsis rapidly increased JA and SA content (Day 3) and later increased ABA levels (Day 5), whereas in Eutrema, ABA levels did not change until Day 5. Untargeted metabolite analysis demonstrated larger responses in Arabidopsis than in Eutrema. In contrast, greater soil drying was needed to initiate partial stomatal closure in Eutrema (Day 6), although decreased water use (when compared to controls) was observed earlier than in Arabidopsis. We hypothesise that growth inhibition is a first response to water deficit in Eutrema. With severe and prolonged drought, conserved metabolic responses (increased sucrose and decreased raffinose and citric acid in both species) co-occurred with near-complete stomatal closure in both species. The different physiological and metabolic responses and their timing allow these species to utilise alternative pathways to physiologically adjust to soil drying, likely reflecting adaptations to their respective niches.

## Acknowledgements

Eutrema seeds were kindly donated by Arie Altman (The Hebrew University of Jerusalem). Annie Storther, Catarina Martins and Mafalda Rodrigues are acknowledged for their valuable assistance with sampling. The York Centre of Excellence in Mass Spectrometry was created thanks to a major capital investment through Science City York, supported by Yorkshire Forward with funds from the Northern Way Initiative, and subsequently received additional support from the EPSRC (EP/K039660/1; EP/M028127/1). CP acknowledges Cândido Pinto Ricardo continuous support. ASM's studentship was funded by the Biotechnology and Biological Sciences Research Council. ED thanks the Daphne Jackson Trust for a Fellowship funded by the Royal Society of Chemistry and the Biotechnology and Biological Sciences Research Council. CA gratefully acknowledges support from Fundação para a Ciência e a Tecnologia (FCT, Portugal) through the FCT Investigator Programme

(IF/00376/2012/CP0165/CT0003). OZ was supported by postdoctoral fellowship from FCT (SFRH/BPD/111693/2015). This work was supported by the ITQB NOVA R&D GREEN-it 'Bioresources for sustainability' (UID/Multi/04551/2013).

## References

- Antonio C, Pinheiro C, Chaves MM, Ricardo CP, Ortuño MF, Thomas-Oates J. (2008). Analysis of carbohydrates in *Lupinus albus* stems on imposition of water deficit, using porous graphitic carbon liquid chromatography-electrospray ionization mass spectrometry. *Journal of Chromatography A* 1187: 111-18.
- Arbona V, Argamasilla R, Gómez-Cadenas A.(2010). Common and divergent physiological, hormonal and metabolic responses of *Arabidopsis thaliana* and *Thellungiella halophila* to water and salt stress. *Journal of Plant Physiology* 167: 1342-50.
- Bechtold U, Penfold CA, Jenkins DJ, *et al.* (2016). Time-series transcriptomics reveals that AGAMOUS-LIKE22 affects primary metabolism and developmental processes in drought-stressed *Arabidopsis*. *The Plant Cell* 28: 345-66.
- Benjamini Y, Hochberg Y. (1995). Controlling the False Discovery Rate: A Practical and powerful approach to multiple testing. *Source Journal of the Royal Statistical Society, Series B (Methodological)*. 57: 289–300.
- Chaves MMM, Costa JMM, Zarrouk O, Pinheiro C, Lopes CMM, Pereira JSS. (2016). Controlling stomatal aperture in semi-arid regions - The dilemma of saving water or being cool? *Plant Science* 251: 54–64.
- Clauw P, Coppens F, Korte A, *et al.* (2016). Leaf growth response to mild drought: natural variation in *Arabidopsis* sheds light on trait architecture. *The Plant Cell* 28: 2417-34.
- Considine MJ, Foyer CH. (2014). Redox regulation of plant development. *Antioxidants & Redox Signaling* 21: 1305-26.
- Daszkowska-Golec A, Szarejko I. (2013). Open or close the gate – stomata action under the control of phytohormones in drought stress conditions. *Frontiers in Plant Science* 4: 138.
- Davies WJ, Mansfield TA, Hetherington AM. (1990). Sensing of soil water status and the regulation of plant growth and development. *Plant, Cell and Environment* 13: 709–19.
- de Ollas C, Dodd IC. (2016). Physiological impacts of ABA-JA interactions under water-limitation. *Plant Molecular Biology*. 91: 641–650.
- Dedrick J. (2007). [Physiological and biochemical responses of Yukon and Shandong](#)

719 *Thellungiella* to water deficits. Master of Science Thesis presented to McMaster University.

720 Dinakar C, Bartels B. (2013) Desiccation tolerance in resurrection plants: new insights from  
721 transcriptome, proteome, and metabolome analysis. *Frontiers in Plant Science* 4: 482.

722 Elsayed AI, Rafudeen MS, Golldack D. (2014). Physiological aspects of raffinose family  
723 oligosaccharides in plants: Protection against abiotic stress. *Plant Biology* 16: 1–8.

724 Farber M, Attia Z, Weiss D. (2016). Cytokinin activity increases stomatal density and  
725 transpiration rate in tomato. *Journal of Experimental Botany* 67:6351-62.

726 Foyer C, Rowell J, Walker D. (1983). Measurement of the ascorbate content of spinach leaf  
727 protoplasts and chloroplasts during illumination. *Planta* 157: 239–44.

728 Gechev TS, Benina M, Obata T, et al. (2013). Molecular mechanisms of desiccation  
729 tolerance in the resurrection glacial relic *Haberlea rhodopensis*. *Cellular and Molecular Life*  
730 *Sciences* 70: 689–709.

731 Gilliham M, Able JA, Roy SJ. (2017). Translating knowledge about abiotic stress tolerance to  
732 breeding programmes. *Plant Journal* 90: 898-917.

733 Golldack D, Li C, Mohan H, Probst N. (2014). Tolerance to drought and salt stress in plants:  
734 Unraveling the signaling networks. *Frontiers in Plants Science* 5:151.

735 Gomez-Cadenas A, Tadeo F, Talon M, Primo-Millo E. (1996). Leaf abscission induced by  
736 ethylene in water-stressed intact seedlings of cleopatra mandarin requires previous abscisic  
737 acid accumulation in roots. *Plant Physiology* 112: 401–08.

738 Gong Q, Li P, Ma S, Indu Rupassara S, Bohnert HJ. (2005). Salinity stress adaptation  
739 competence in the extremophile *Thellungiella halophila* in comparison with its relative  
740 *Arabidopsis thaliana*. *The Plant Journal* 44: 826-39.

741 Granda E, Camarero JJ. (2017). Drought reduces growth and stimulates sugar accumulation:  
742 new evidence of environmentally driven non-structural carbohydrate use. *Tree Physiology*  
743 *37: 997-1000.*

744 Ha S, Vankova R, Yamaguchi-Shinozaki K, Shinozaki K, Tran L-SP. (2012). Cytokinins:  
745 metabolism and function in plant adaptation to environmental stresses. *Trends in Plant*  
746 *Science* 17: 172-79.

747 Harris MJ, Outlaw WH. (1991). Rapid adjustment of guard-cell abscisic acid levels to current  
748 leaf-water status. *Plant Physiology*. 95: 171-73.

749 Hummel I, Pantin F, Sulpice R, Piques M, Rolland G, Dauzat M, Christophe A, Pervent M,  
750 Bouteillé M, Stitt M, Gibon Y, Mulle B. (2010). *Arabidopsis* plants acclimate to water

deficit at low cost through changes of carbon usage: an integrated perspective using growth, metabolite, enzyme, and gene expression analysis. *Plant Physiology* 154: 357-72.

Jameson PE. (2017). Cytokinins. In: Thomas B (ed), Murray BG (ed), Murphy DJ (ed). *Encyclopedia of Applied Plant Sciences*, 2<sup>nd</sup> edn, Academic Press and Elsevier, Oxford, Vol 1, pp391–402.

Kalaji HM, Schansker G, Brestic M, *et al.* (2017). Frequently asked questions about chlorophyll fluorescence, the sequel. *Photosynthesis Research* 132: 13-66

Khokon MAR, Salam MA, Jammes F, Ye W, Hossain MA, Okuma E, Nakamura Y, Mori IC, Kwak JM, Murata Y. (2017). MPK9 and MPK12 function in SA-induced stomatal closure in *Arabidopsis thaliana*. *Bioscience, Biotechnology, and Biochemistry* 81:1394-1400.

Kieber JJ, Schaller GE. (2014). Cytokinins. *The Arabidopsis Book* 12: e0168.

Koffler BE, Luschin-Ebengreuth N, Stabentheiner E, Müller M, Zechmann B. (2014). Compartment specific response of antioxidants to drought stress in *Arabidopsis*. *Plant Science* 227: 133-44

Koornneef M, Meinke D. (2010). The development of *Arabidopsis* as a model plant. *The Plant Journal* 61: 909-21.

Kosma DK, Bourdenx B, Bernard A, Parsons EP, Lü S, Joubès J, Jenks MA. (2009). The impact of water deficiency on leaf cuticle lipids of *Arabidopsis*. *Plant Physiology* 151: 1918-29

Lee YP, Funk C, Erban A, Kopka J, Köhl KI, Zuther E, Hinch DK. (2016). Salt stress responses in a geographically diverse collection of *Eutrema/Thellungiella* spp. accessions. *Functional Plant Biology* 43: 590-606.

Lichtenthaler HK, Buschmann C. (2001). Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy. *Current Protocols in Food Analytical Chemistry*. F:F4:F4.3

Lü S, Zhao H, Marais DLD, *et al.* (2012). *Arabidopsis ECERIFERUM9* involvement in cuticle formation and maintenance of plant water status. *Plant Physiology* 159: 930-44.

MacLeod MJ, Dedrick J, Ashton C, Sung WW, Champigny MJ, Weretilnyk EA. (2015). Exposure of two *Eutrema salsugineum* (*Thellungiella salsuginea*) accessions to water deficits reveals different coping strategies in response to drought. *Physiologia Plantarum* 155: 267-80.

Meyre D, Leonardi A, Brisson G, Vartanian N. (2011). Drought-adaptive mechanisms involved in the escape/tolerance strategies of *Arabidopsis Landsberg erecta* and *Columbia*

ecotypes and their F1 reciprocal progeny. *Journal of Plant Physiology* 158: 1145-52.

Miura K, Tada Y. (2014). Regulation of water, salinity, and cold stress responses by salicylic acid. *Frontiers in Plant Science* 5: 4.

Montesinos-Navarro A, Wig J, Xavier Pico F, Tonsor SJ. (2011). *Arabidopsis thaliana* populations show clinal variation in a climatic gradient associated with altitude. *New Phytologist* 189: 282-94.

Moyankova D, Mladenov P, Berkov S, Peshev D, Georgieva D, Djilianov D. (2014). Metabolic profiling of the resurrection plant *Haberlea rhodopensis* during desiccation and recovery. *Physiologia Plantarum* 152: 675-87.

Muller J, Sprenger N, Bortlik K, Boller T, Wiemken A. (1997). Desiccation increases sucrose levels in *Ramonda* and *Haberlea*, two genera of resurrection plants in the Gesneriaceae. *Physiologia Plantarum* 100: 153–158.

Müller M, Munné-Bosch S. (2011). Rapid and sensitive hormonal profiling of complex plant samples by liquid chromatography coupled to electrospray ionization tandem mass spectrometry. *Plant Methods* 7: 37.

Müller M, Munné-Bosch S. (2015). Ethylene response factors: A key regulatory hub in hormone and stress signaling. *Plant Physiology* 169: 32-41.

Munné-Bosch S, Müller M. (2013). Hormonal cross-talk in plant development and stress responses. *Frontiers in Plant Science* 4 :529.

Muñoz-Espinoza VA, López-Climent MF, Casaretto JA, Gómez-Cadenas A. (2015). Water stress responses of tomato mutants impaired in hormone biosynthesis reveal abscisic acid, jasmonic acid and salicylic acid interactions. *Frontiers in Plant Science* 6: 997.

Nguyen KH, Ha CV, Nishiyama R, et al. (2016). *Arabidopsis* type B cytokinin response regulators ARR1, ARR10, and ARR12 negatively regulate plant responses to drought. *Proceedings of the National Academy of Sciences* 113: 3090-95.

Nishiyama R, Watanabe Y, Fujita Y, Le DT, et al. (2011). Analysis of cytokinin mutants and regulation of cytokinin metabolic genes reveals important regulatory roles of cytokinins in drought, salt and abscisic acid responses, and abscisic acid biosynthesis. *The Plant Cell* 23: 2169-83.

Noctor G, Mhamdi A, Foyer CH. (2014). The roles of reactive oxygen metabolism in drought: Not so cut and dried. *Plant Physiology* 164: 1636-48.

Orsini F, D'Urzo MP, Inan G, Serra S, Ha Oh D, Mickelbart MV, Consiglio F, Li X, Jeong JC, Yun DJ, Bohnert HJ, Bressan RA, Maggio1 A. (2010). A comparative study of salt

tolerance parameters in 11 wild relatives of *Arabidopsis thaliana*. Journal of Experimental Botany 61: 3787-98.

Osakabe Y, Osakabe K, Shinozaki K, Tran L-SP. (2014). Response of plants to water stress. Frontiers in Plant Science 5: 86.

Peters S, Mundree SG, Thomson JA, Farrant JM, Keller F. (2007). Protection mechanisms in the resurrection plant *Xerophyta viscosa* (Baker): both sucrose and raffinose family oligosaccharides (RFOs) accumulate in leaves in response to water deficit. Journal of Experimental Botany 58: 1947-56.

Pilarska M, Wiciarz M, Ivan Jajić I, Kozieradzka-Kiszkurno M, Dobrev P, Vanková R, Niewiadomska E. (2016). A different pattern of production and scavenging of reactive oxygen species in halophytic *Eutrema salsugineum* (*Thellungiella salsuginea*) plants in comparison to *Arabidopsis thaliana* and its relation to salt stress signaling. Frontiers in Plant Science 7: 1179.

Pinheiro C, Antonio C, Ortuno MF, Dobrev PI, Hartung W, Thomas-Oates J, Ricardo CP, Vankova R, Chaves MM, Wilson JC. (2011). Initial water deficit effects on *Lupinus albus* photosynthetic performance, carbon metabolism, and hormonal balance: metabolic reorganization prior to early stress responses. Journal of Experimental Botany 62: 4965-74.

Pinheiro C, Chaves MM, Ricardo CP. (2001). Alterations in carbon and nitrogen metabolism induced by water deficit in the stems and leaves of *Lupinus albus* L. Journal of Experimental Botany 52: 1063-70.

Pinheiro C, Chaves MM. (2011). Photosynthesis and drought: Can we make metabolic connections from available data? Journal of Experimental Botany 62: 869-82.

Pinheiro C, Passarinho JA, Ricardo CP. (2004). Effect of drought and rewatering on the metabolism of *Lupinus albus* organs. Journal of Plant Physiology 161: 1203-10.

Piquerez SJM, Harvey SE, Beynon JL, Ntoukakis V. (2014). Improving crop disease resistance: lessons from research on Arabidopsis and tomato. Frontiers in plant science 5: 671.

Puértolas J, Larsen EK, Davies WJ, Dodd IC. (2017). Applying 'drought' to potted plants by maintaining suboptimal soil moisture improves plant water relations. Journal of Experimental Botany 68: 2413-24.

Queval G, Noctor G. (2007). A plate reader method for the measurement of NAD, NADP, glutathione, and ascorbate in tissue extracts: Application to redox profiling during Arabidopsis rosette development. Analytical Biochemistry 363: 58-69.

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rivas-San Vicente M, Plasencia J. (2011). Salicylic acid beyond defence: its role in plant growth and development. *Journal of Experimental Botany* 62: 3321-38.

Rivero RM, Kojima M, Gepstein A, Sakakibara H, Mittler R, Gepstein S, Blumwald E. (2007). Delayed leaf senescence induces extreme drought tolerance in a flowering plant. *Proceedings of the National Academy of Sciences* 104: 19631-36.

Ruan YL. (2014). Sucrose metabolism: gateway to diverse carbon use and sugar signaling. *Annual Review of Plant Biology* 65: 33-67.

Rusilowicz M, Dickinson M, Charlton A, O’Keefe S, Wilson J. (2016). A batch correction method for liquid chromatography–mass spectrometry data that does not depend on quality control samples. *Metabolomics* 12: 56.

Sack L, John GP, Buckley TN. (2018). ABA accumulation in dehydrating leaves is associated with decline in cell volume not turgor pressure. *Plant Physiology* 176: 489-95.

Skirycz A, Vandenbroucke K, Clauw P, et al. (2011). Survival and growth of *Arabidopsis* plants given limited water are not equal. *Nat Biotechnology* 29: 212-14.

Smith A, Stitt M (2007) Coordination of carbon supply and plant growth. *Plant Cell & Environment* 30: 1126–49.

Sun X, Luo X, Sun M, et al. (2014). A *Glycine soja* 14-3-3 protein GsGF140 participates in stomatal and root hair development and drought tolerance in *Arabidopsis thaliana*. *Plant and Cell Physiology* 55: 99-118.

Taji T, Ohsumi C, Iuchi S, Seki M, Kasuga M, Kobayashi M, Yamaguchi-Shinozaki K, Shinozaki K. (2002). Important roles of drought- and cold-inducible genes for galactinol synthase in stress tolerance in *Arabidopsis thaliana*. *The Plant Journal* 29: 417-26.

Taji T, Seki M, Satou M, Sakurai T, Kobayashi M, Ishiyama K, Narusaka Y, Narusaka M, Zhu JK, Shinozaki K. (2004). Comparative genomics in salt tolerance between *Arabidopsis* and *Arabidopsis*-related halophyte salt cress using *Arabidopsis* microarray. *Plant Physiology* 135: 1697-709.

Tardieu F. (2012). Any trait or trait-related allele can confer drought tolerance: just design the right drought scenario. *Journal of Experimental Botany* 63: 25-31.

Tardieu F. (2016). Too many partners in root-shoot signals. Does hydraulics qualify as the only signal that feeds back over time for reliable stomatal control? *New Phytologist* 212: 802-04.



- Tran LSP, Urao T, Qin F, Maruyama K, Kakimoto T, Shinozaki K, Yamaguchi-Shinozaki K. (2007). Functional analysis of AHK1/ATHK1 and cytokinin receptor histidine kinases in response to abscisic acid, drought, and salt stress in *Arabidopsis*. *Proceedings of the National Academy of Sciences* 104: 20623-28.
- Turner NC, Abbo S, Berger JD, Chaturvedi SK, French RJ, Ludwig C, et al. (2007). Osmotic adjustment in chickpea (*Cicer arietinum* L.) results in no yield benefit under terminal drought. *Journal of Experimental Botany* 58: 187-94.
- Uarrota VG, Stefen DLV, Leolato LS, Gindri DM, Nerling D. (2018). Revisiting carotenoids and their role in plant stress responses: From biosynthesis to plant signaling mechanisms during stress. In: Gupta D., Palma J., Corpas F. (eds) *Antioxidants and Antioxidant Enzymes in Higher Plants*. Springer, Cham
- Urano K, Maruyama K, Jikumaru Y, Kamiya Y, Yamaguchi-Shinozaki K, Shinozaki K. (2017). Analysis of plant hormone profiles in response to moderate dehydration stress. *The Plant Journal* 90: 17-36.
- Wehrens R, Hageman JA, van Eeuwijk F, Kooke R, Flood PJ, Wijnker E, Keurentjes JJ, Lommen A, van Eekelen HD, Hall RD, Mumm R. (2016). Improved batch correction in untargeted MS-based metabolomics. *Metabolomics* 12: 88.
- Whittaker A, Martinelli T, Farrant JM, Bochicchio A, Vazzana C. (2007). Sucrose phosphate synthase activity and the co-ordination of carbon partitioning during sucrose and amino acid accumulation in desiccation-tolerant leaf material of the C4 resurrection plant *Sporobolus stapfianus* during dehydration. *Journal of Experimental Botany* 58: 3775-87.
- Wiley E, Brent Helliker B. (2012). A re- evaluation of carbon storage in trees lends greater support for carbon limitation to growth. *The New Phytologist* 195: 285-89.
- Xu X, Feng J, Lü S, Lohrey GT, An H, Zhou Y, Jenks MA. (2014). Leaf cuticular lipids on the Shandong and Yukon ecotypes of saltwater cress, *Eutrema salsugineum* , and their response to water deficiency and impact on cuticle permeability. *Physiologia Plantarum* 151: 446-58.
- Xu Y, Burgess P, Huang B. (2017). Transcriptional regulation of hormone-synthesis and signaling pathways by overexpressing cytokinin-synthesis contributes to improved drought tolerance in creeping bentgrass. *Physiologia Plantarum* 161: 235-56
- Zhao Y, Chan Z, Gao J, et al. (2016). ABA receptor PYL9 promotes drought resistance and leaf senescence. *Proceedings of the National Academy of Sciences* 113: 1949-54
- Zhu J-K. (2015). The Next Top Models: Extreme Farming. *Cell* 163: 18–20.



## Figure Legends

Figure 1. Soil water content (SWC, %) after imposing water deficit and on re-watering (shaded area). SWC is shown before (symbols) and after (dotted lines) partial water replacement (to regulate the rate of soil water depletion). Data show the means  $\pm$  standard error of 6 pots (except Day 1 with 5 pots). For pre-irrigation SWC, significance levels were calculated using the Mann–Whitney U test. Data differing significantly from Day 0 are denoted by asterisks (\*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ ).

Figure 2. Leaf stomatal conductance (as a % of the control plants) plotted against SWC. Mean values (of 3 to 5 biological replicates) are shown with only positive standard errors for clarity. Significant results, as determined by Mann-Whitney U test, are denoted by asterisks (\*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ ). ANCOVA for each main effect (treatment and species) and their interaction is presented in supplementary Fig S4B.

Figure 3. PCA plots showing the scores for the first two principal components obtained for the untargeted metabolomic analysis coloured by experimental group and the day of harvest, for (A) Arabidopsis and (B) Eutrema. For both plant species, the data have been scaled to unit variance and control corrected. In the case of Eutrema only, batch correction has also been performed.

Figure 4. PCA scores plots for the first two principal components obtained from scaled early-stress observations (Days 1, 3 and 5) in the untargeted analysis after control correction for (A) Arabidopsis and (B) Eutrema. The observations are coloured according to the day of harvest, showing that the clustering of observations is related to drought duration.

Figure 5. Dendrogram obtained from hierarchical clustering of the 46 time-series selected by the iterative k-means analysis of the metabolite data. The clusters are coloured and annotated A-I according to the clusters identified in the k-means analysis (supplementary Fig S5). Metabolites within clusters are labelled as follows: S= sucrose; R = raffinose; St = stachyose; CA = citric acid; U = unassigned hexose disaccharide.

Figure 6. Biochemical parameters with a statistically significant change in early drought stress in Arabidopsis but not in Eutrema. The mean difference from well-watered plants for leaf RWC and the hormones ABA, JA, SA and GA24 are shown with error bars representing the standard error. The mean values after control correction (i.e. the mean value for the controls has been subtracted) are represented. Arabidopsis: dark grey; Eutrema: light grey. Significant results are shown in Table 3.

Figure 7. Biochemical parameters with a significant change in early stress in Eutrema but not in Arabidopsis. The mean measurement for osmotic potential, DHA, AscA, 2iP and GA9 are shown with error bars representing the standard error of the observations. The mean values after control correction (i.e. the mean value for the controls has been subtracted) are represented. Arabidopsis: dark grey; Eutrema: light grey. Significant results are shown in Table 3.

Figure 8. Cytokinins during early (Days 1, 3, 5) and late (Day 12) stress and on re-watering (Day 13). Mean values and  $\pm$  standard error of 6 biological replicates (except for Day 1 where  $n=5$ ). The mean values after control correction (i.e. the mean value for the controls has been subtracted) are represented. In Arabidopsis, ZR, 2iP and IPA peak at late stress and decrease on re-watering. However, in Eutrema, these hormones show a slight decrease in late stress and increase dramatically on re-watering. Arabidopsis: dark grey; Eutrema: light grey. Significant results are shown in Table 2.

**Supplementary table S1.** Biochemical parameters for both control (WW) and stressed (WD) observations in Arabidopsis. Data are the means  $\pm$  standard error of 6 biological replicates, except for day 1 ( $n = 5$ ). Asterisks in the third row show parameters with a significant difference between WW and WD for a particular day (obtained using Mann-Whitney tests). Asterisks in the final column for each day show days that are significantly different from earlier days (using Tukey's HSD test) with the specific days given in parentheses. Here, asterisks denote \*\*\*  $p < 0.001$ , \*\*  $p < 0.01$  and \*  $p < 0.05$ .

**Supplementary table S2.** Biochemical parameters for both control (WW) and stressed (WD) observations in Eutrema. Data are the means  $\pm$  standard error of 6 biological replicates, except for day 1 ( $n = 5$ ). Asterisks in the third row show parameters with a significant difference between WW and WD for a particular day (obtained using Mann-Whitney tests). Asterisks in the final column for each day show days that are significantly different from earlier days (using Tukey's HSD test) with the specific days given in parentheses. Here, asterisks denote \*\*\*  $p < 0.001$ , \*\*  $p < 0.01$  and \*  $p < 0.05$ .

**Supplementary table S3.** Biochemical parameters for both control (WW) and stressed (WD) observations in Arabidopsis. Samples were control-corrected (see Methods section). Data shown are the means  $\pm$  standard error of 6 biological replicates, except for day 1 ( $n = 5$ ).

**Supplementary table S4.** Biochemical parameters for both control (WW) and stressed (WD) observations in Eutrema. Samples were control corrected (see). Data shown are the means  $\pm$  standard error of 6 biological replicates, except for day 1 ( $n = 5$ ).

**Supplementary Figure S1.** Preliminary drought assay. **A** - Soil water content (SWC, %) progression during the assay for Eutrema and Arabidopsis; **B** - Leaf stomatal conductance (% of the control gs) as a function of the SWC. For controls, percentage gs was calculated relative to day 0; for treatments, percentage gs was calculated relative to the control for the same day. The 80 % gs level was achieved on different days: by day 4 in Arabidopsis and by day 6 in Eutrema; **C** - Regression line fit % gs vs soil water content. Each point represents a single measurement and p-values were determined by ANCOVA for each main effect (treatment and species) and their interaction (ns: not significant; #:  $p < 0.1$ ; \*\*\*:  $p < 0.001$ ).

**Supplementary Figure S2.** PCA plots showing the scores for the first two principal components obtained for the Eutrema data after scaling to unit variance with the observations coloured by batch. **A-** Before batch correction, clustering within batches can be seen and, in particular, batches 7 and 8 cluster separately. **B-** After batch correction, differences between batches are no longer apparent.

**Supplementary Figure S3.** PCA scores for the first two principal components obtained for the Arabidopsis data after scaling to unit variance. The observations are coloured by data collection batch and no obvious differences between batches can be seen, so that batch correction is not necessary.

**Supplementary Figure S4. A -** Leaf stomatal conductance of Arabidopsis and Eutrema after imposing water deficit and on re-watering (shaded area); **B -** Regression line fitting % gs vs soil water content. Each point represents a single measurement and p-values were determined by ANCOVA for each main effect (treatment and species) and their interaction (ns: not significant; \*\*\*:  $p < 0.001$ ).

**Supplementary Figure S5.** The nine clusters obtained with k-means analysis of the 46 time-series remaining after iterative filtering of the metabolite data. Cluster A and cluster B include several sucrose species. Cluster C includes raffinose and cluster D includes citric acid.

**Supplementary Figure S6.** Heatmap showing the similarity of the 46 time-series selected by iterative k-means analysis of the metabolite data. Metabolites are labelled as follows: S= sucrose; R = raffinose; St = stachyose; CA = citric acid; U = unassigned hexose disaccharide.

**Supplementary Figure S7.** PCA plots of the biochemical parameters for both control (WW) and treatment (WD) observations in Arabidopsis and Eutrema after control correction. (A) unscaled variables; (B) scaled variables.

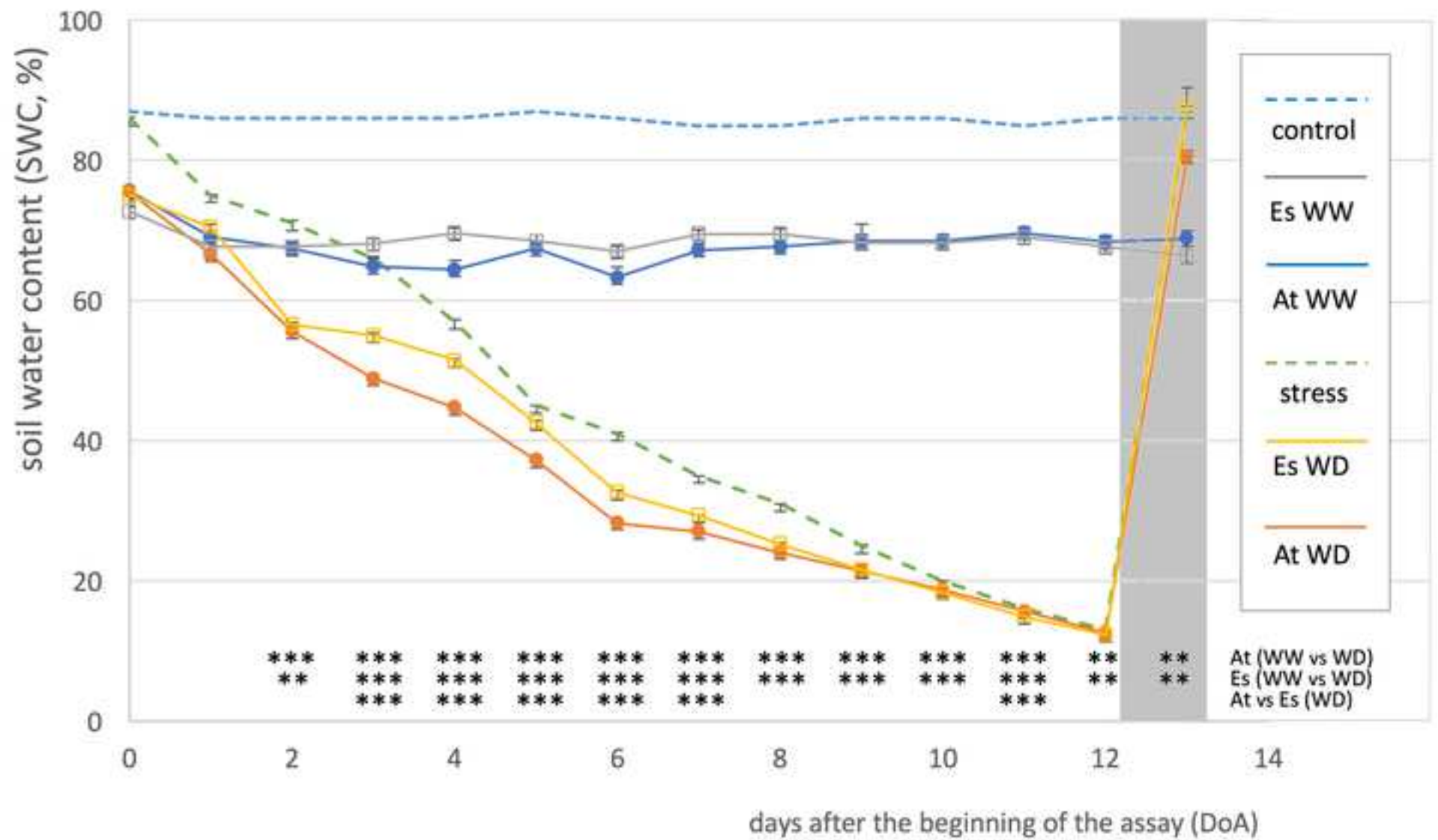
**Supplementary Figure S8.** Line plots showing physiological and biochemical parameters in early-drought stress (days 1, 3 and 5) after control correction. Error bars show the standard error between observations ( $n = 6$  biological replicates, except for day 1,  $n = 5$ ). Dark grey: Arabidopsis; light grey: Eutrema. ANOVA results are presented in Table 3.

**Supplementary Figure S9.** Bar charts showing physiological and biochemical parameters in

early- (days 1, 3 and 5) and late-drought stress and on re-watering (day 13) after control correction. Error bars show the standard error between observations (n = 6 biological replicates, except for day 1, n = 5). Dark grey: Arabidopsis; light grey: Eutrema. ANOVA results are presented in Table 2.

Figure1

[Click here to access/download;Figure;EvennewerFigure1\\_20180907.tiff](#)



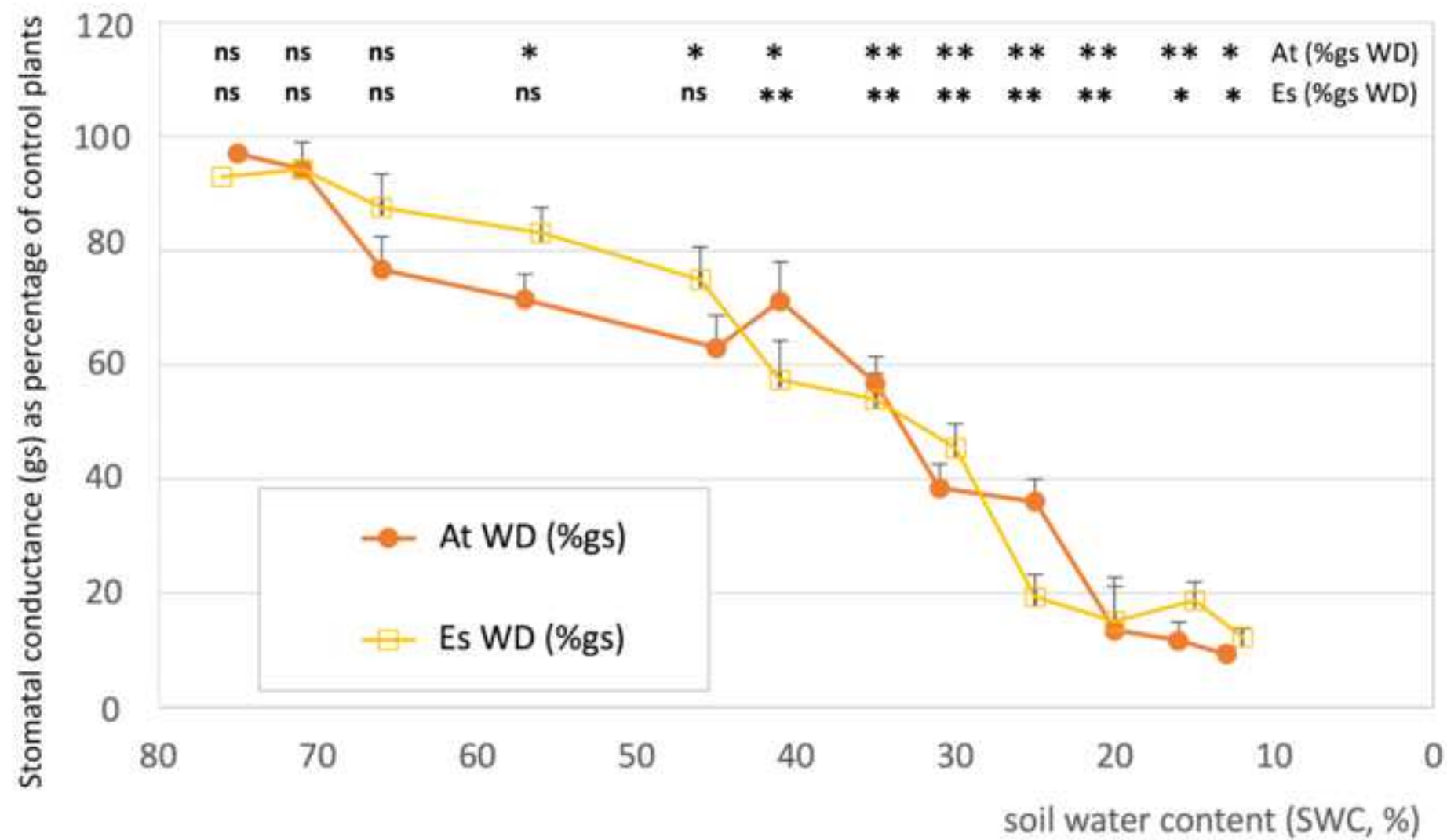


Figure3

[Click here to access/download;Figure;newFig3HR.tiff](#)

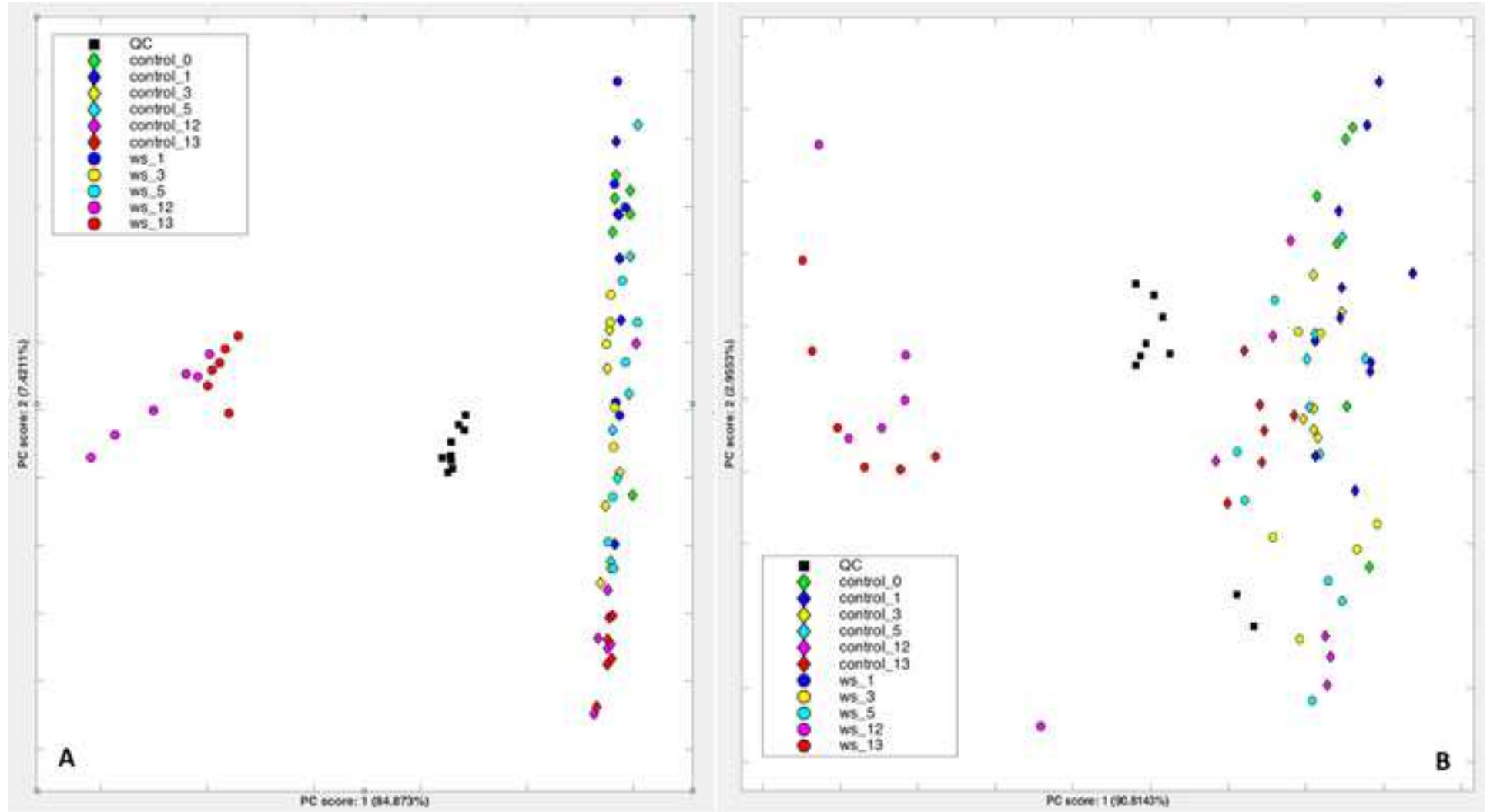




Figure4

[Click here to access/download;Figure;newFig4HR.tiff](#)

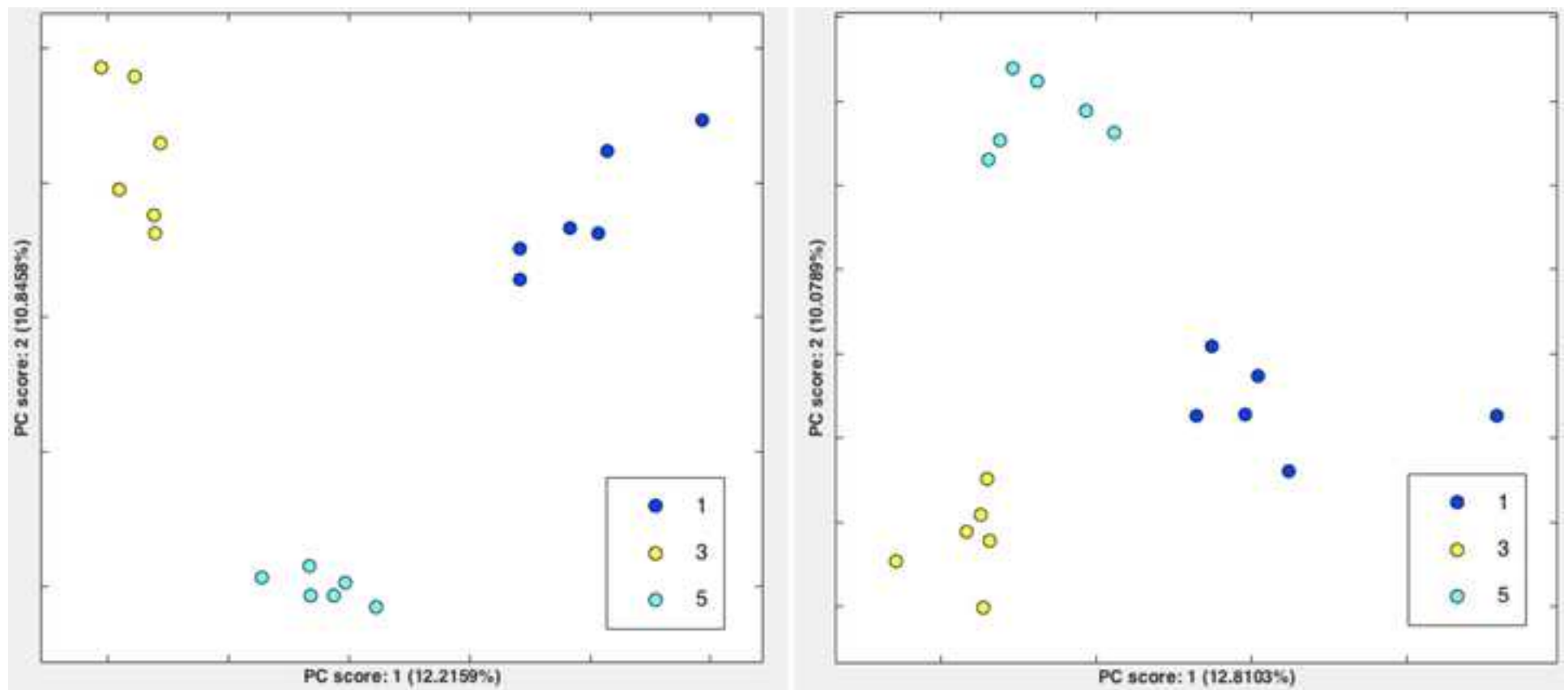
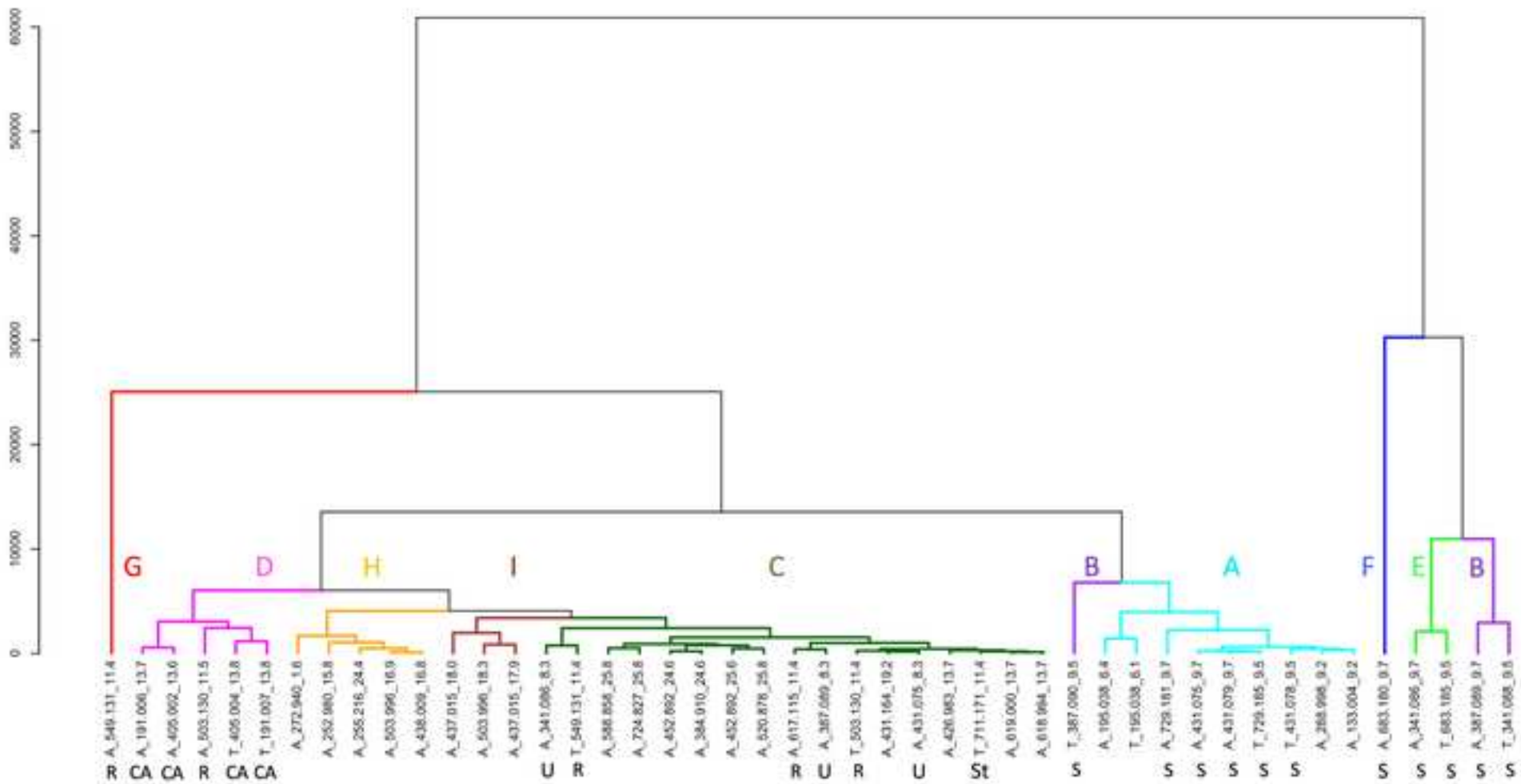
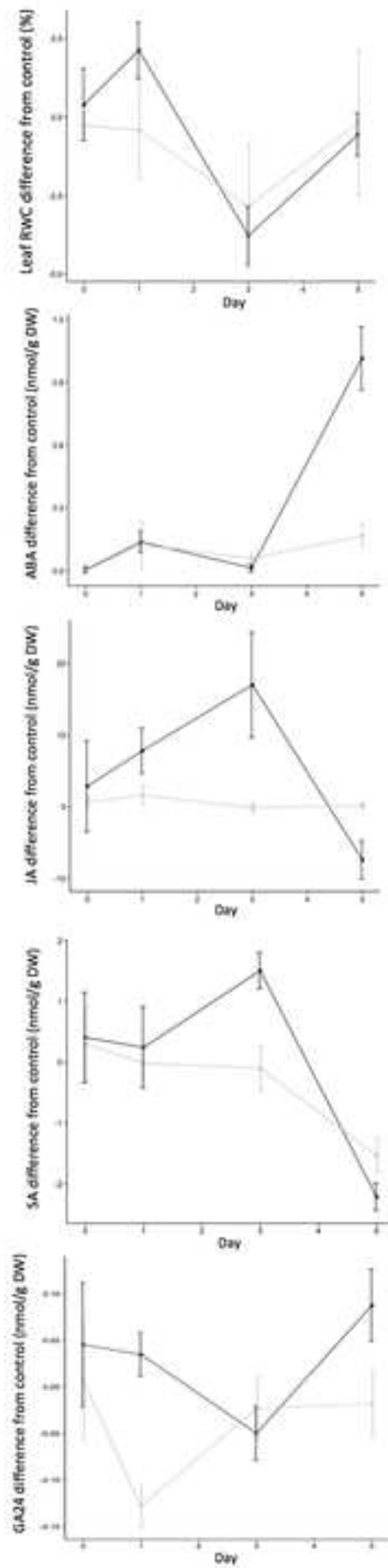


Figure5





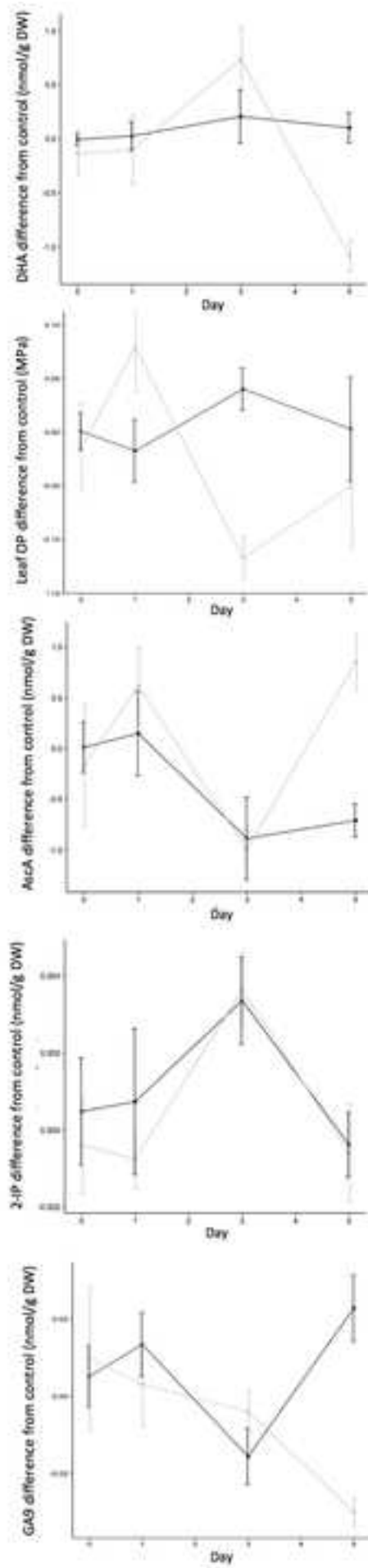
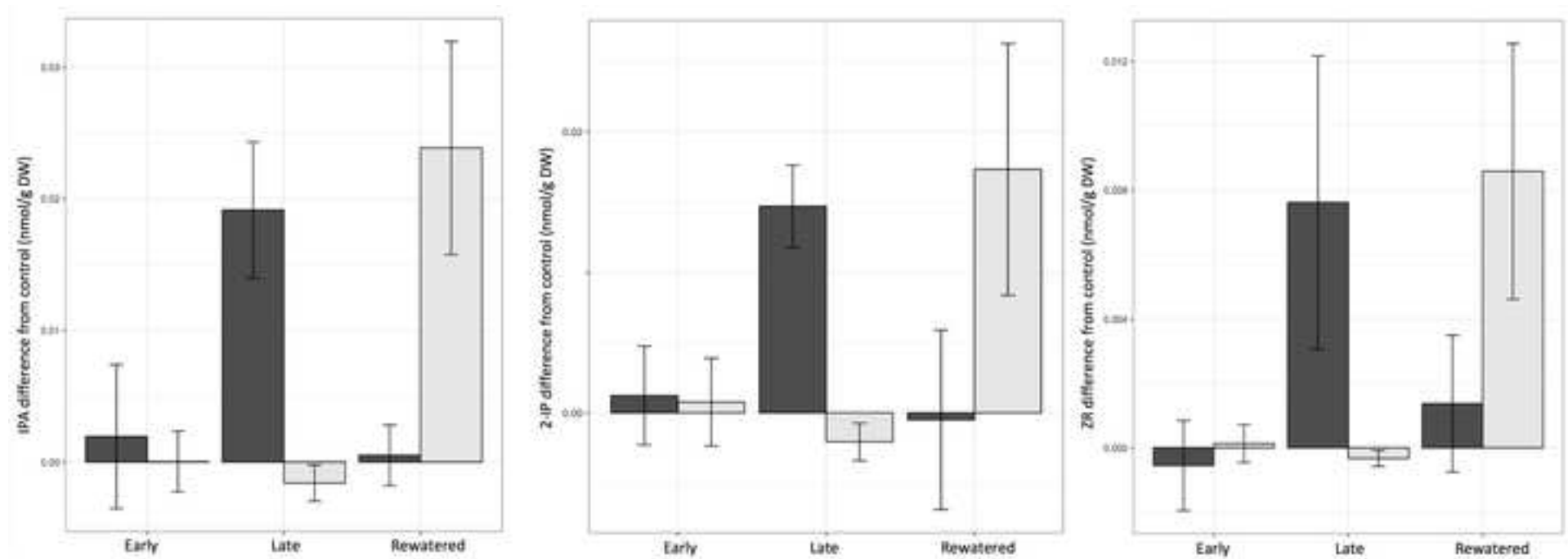


Figure8



**Table 1:** Molecular forms assigned to sucrose, raffinose and citric acid that were significantly different ( $p < 0.001$ ) between late drought-stressed and rewatering observations (days 12 or 13) and the corresponding controls.

Compound	Molecular form	<i>m/z</i>
sucrose	[M-H] <sup>-</sup>	341.087
sucrose	[M+HCOO] <sup>-</sup>	387.092
sucrose	[M-2H+2Na+HCOO] <sup>-</sup>	431.092
sucrose	[2M-H] <sup>-</sup>	683.181
sucrose	[2M-HCOO] <sup>-</sup>	729.186
raffinose	[M-H] <sup>-</sup>	503.126
raffinose	[M-HCOO] <sup>-</sup>	549.131
raffinose	[M+HCOONa+HCOO] <sup>-</sup>	617.119
citric acid	[M-H] <sup>-</sup>	191.006
citric acid	[2M-2H+Na] <sup>-</sup>	405.002

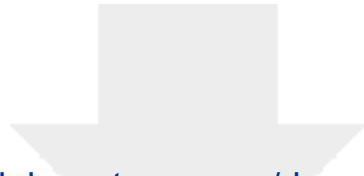
**Table 2.** Representation of ANOVA results after Tukey's HSD correction for pairwise testing between early stress (combined days 1, 3 and 5), late stress (day 12) and re-watered (day 13) observations. Separate ANOVA models were obtained for each species. Light green represents  $p < 0.05$ , mid-green  $p < 0.01$  and dark green  $p < 0.001$ . White cells indicate no significant difference at the 95 % confidence level. Carotenoids, DHA, IAA, DHZ DHZR, GA19, GA20 and GA24 were measured, but omitted from the table as no significant difference between groups was found for either plant species. Arrows denote an increase (↑) or decrease (↓) in measurement.

Variable	Species	Early - late	Late - rewatered
Biomass	At	↓	
	Th	↓	
Root RWC	At	↓	↑
	Th	↓	↑
Leaf RWC	At	↓	↑
	Th	↓	↑
Starch	At	↓	
	Th	↓	↑
OP	At	↓	
	Th	↓	
OA	At		↓
	Th	↑	↓
OP100	At		↓
	Th	↑	↓
PSII	At	↓	
	Th	↓	↑
Chla	At	↓	↑
	Th	↓	
Chlb	At		
	Th		↓
AscA	At	↓	↓
	Th	↓	
ABA	At		
	Th	↑	
IAA	At		
	Th		
IPA	At	↑	↓
	Th		↑
2-IP	At	↑	↓
	Th		↑
ZR	At	↑	↓
	Th		↑
Z	At		
	Th		↑
DHZ	At		
	Th		
JA	At	↓	
	Th	↓	
SA	At	↓	↓
	Th	↓	↓
ACC	At		
	Th	↑	↓

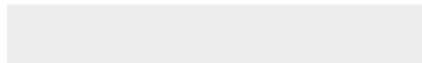


**Table 3.** Representation of ANOVA results after Tukey’s HSD correction for pairwise testing between early stress observations. Light green represents  $p < 0.05$ , mid-green  $p < 0.01$  and dark green  $p < 0.001$ . White cells indicate no significant difference at the 95% confidence level. Variables that were measured, but for which no significant difference between groups was found for either plant species were omitted from the table. Arrows denote an increase (↑) or decrease (↓) in measurement. Plots are shown in Fig. 7 and 8 and supplementary Fig. S7.

Variable	Species	Day 1 - day 3	Day 3 - day 5
Leaf RWC	At	↓	↑
	Th		
ABA	At		↑
	Th		
JA	At		↓
	Th		
SA	At		↓
	Th		↓
OP100	At	↑	
	Th		
OP	At		
	Th	↓	
DHA	At		
	Th		↓
AscA	At		
	Th	↓	↑
2-IP	At		
	Th	↑	↓
GA24	At		↑
	Th		
GA9	At	↓	↑
	Th		



Click here to access/download  
**Supplementary Material**  
SF1HR\_20180909.tiff





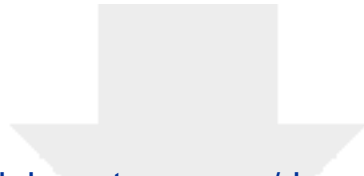
[Click here to access/download](#)  
**Supplementary Material**  
SF2HR.tiff



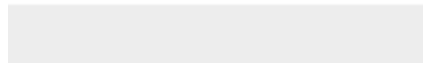


[Click here to access/download](#)  
**Supplementary Material**  
SF3HR.tiff





Click here to access/download  
**Supplementary Material**  
SF4HR\_20180907.tiff





[Click here to access/download](#)  
**Supplementary Material**  
SF5HR.tiff





Click here to access/download  
**Supplementary Material**  
SF6HR.tiff







Click here to access/download  
**Supplementary Material**  
SF7HR.tiff





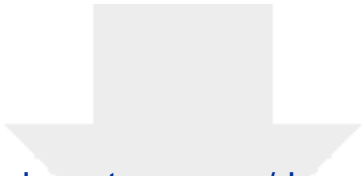
Click here to access/download  
**Supplementary Material**  
SF8HR.tiff



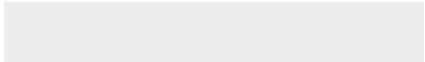


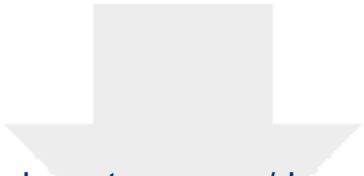
[Click here to access/download](#)  
**Supplementary Material**  
SF9HR.tiff





Click here to access/download  
**Supplementary Material**  
tables S1 & S2\_MannW\_v9.xlsx





[Click here to access/download](#)

**Supplementary Material**  
sup tables S3 & S4\_v3.xlsx

